

Light Dark Matter and Proton Beam Dumps

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University of Washington

New Perspectives on Dark Matter Workshop

April 28, 2014

Outline

(Light) DM motivation and basic experimental idea

Existing constraints, benchmark model

How to use proton beams to find light DM

Theory/Experiment outlook

Based on

Batell, Pospelov, Ritz 0906.5614

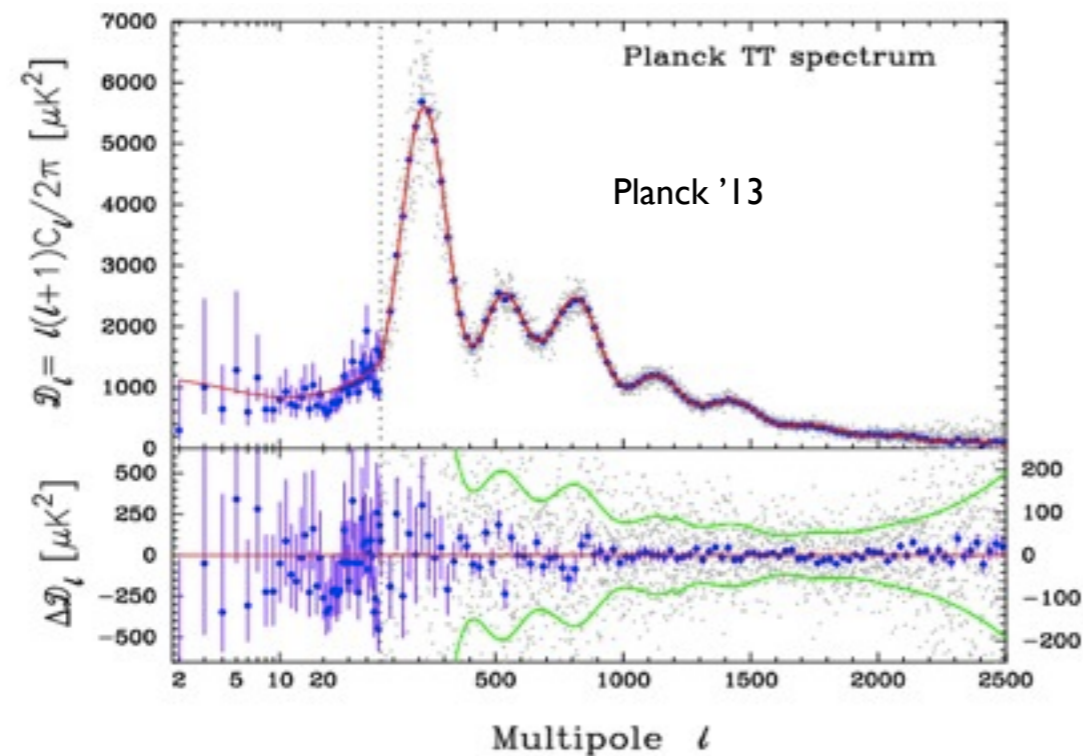
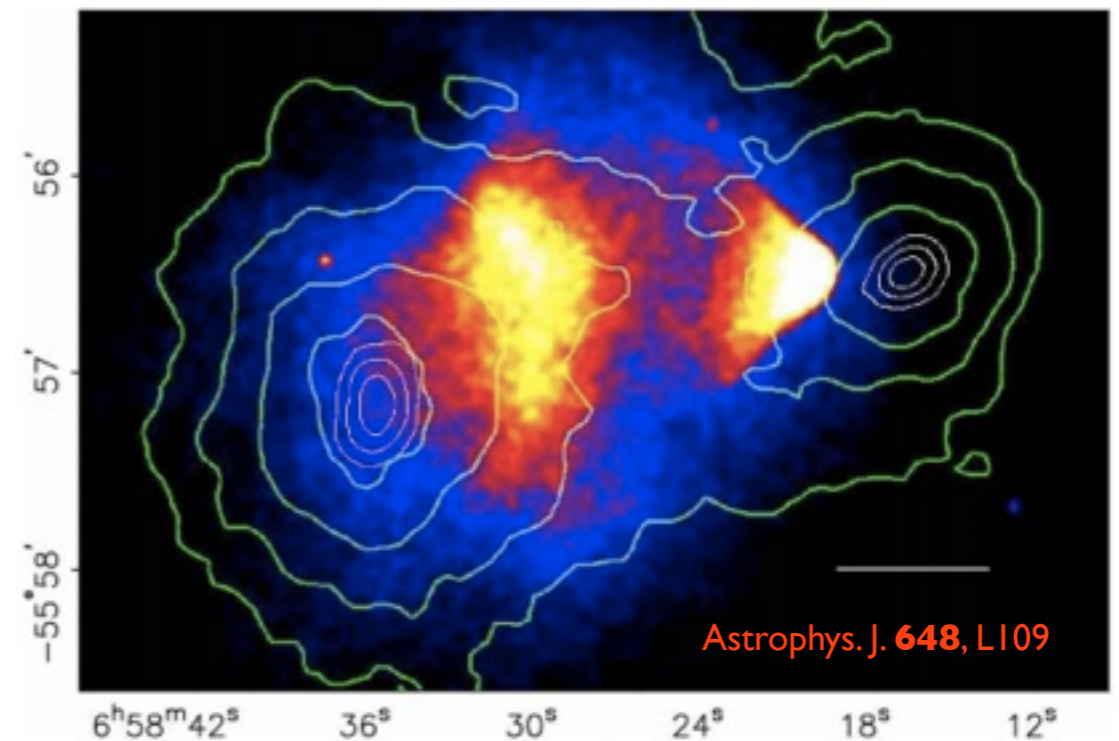
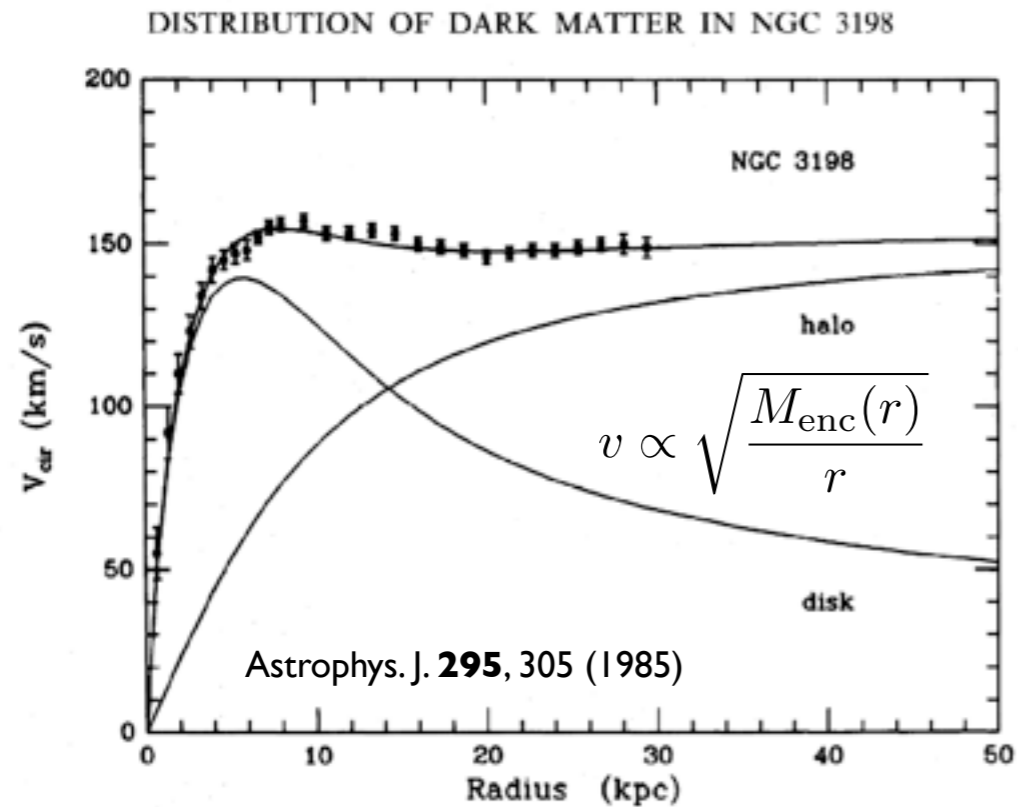
deNiverville, Pospelov, Ritz 1107.4580

deNiverville, DM, Ritz 1205.3499

Low Mass WIMP Searches with a Neutrino
Experiment: A Proposal for Further MiniBooNE
Running [Aguilar-Arevalo et al. 1211.2258]

Batell, deNiverville, DM, Pospelov, Ritz in preparation

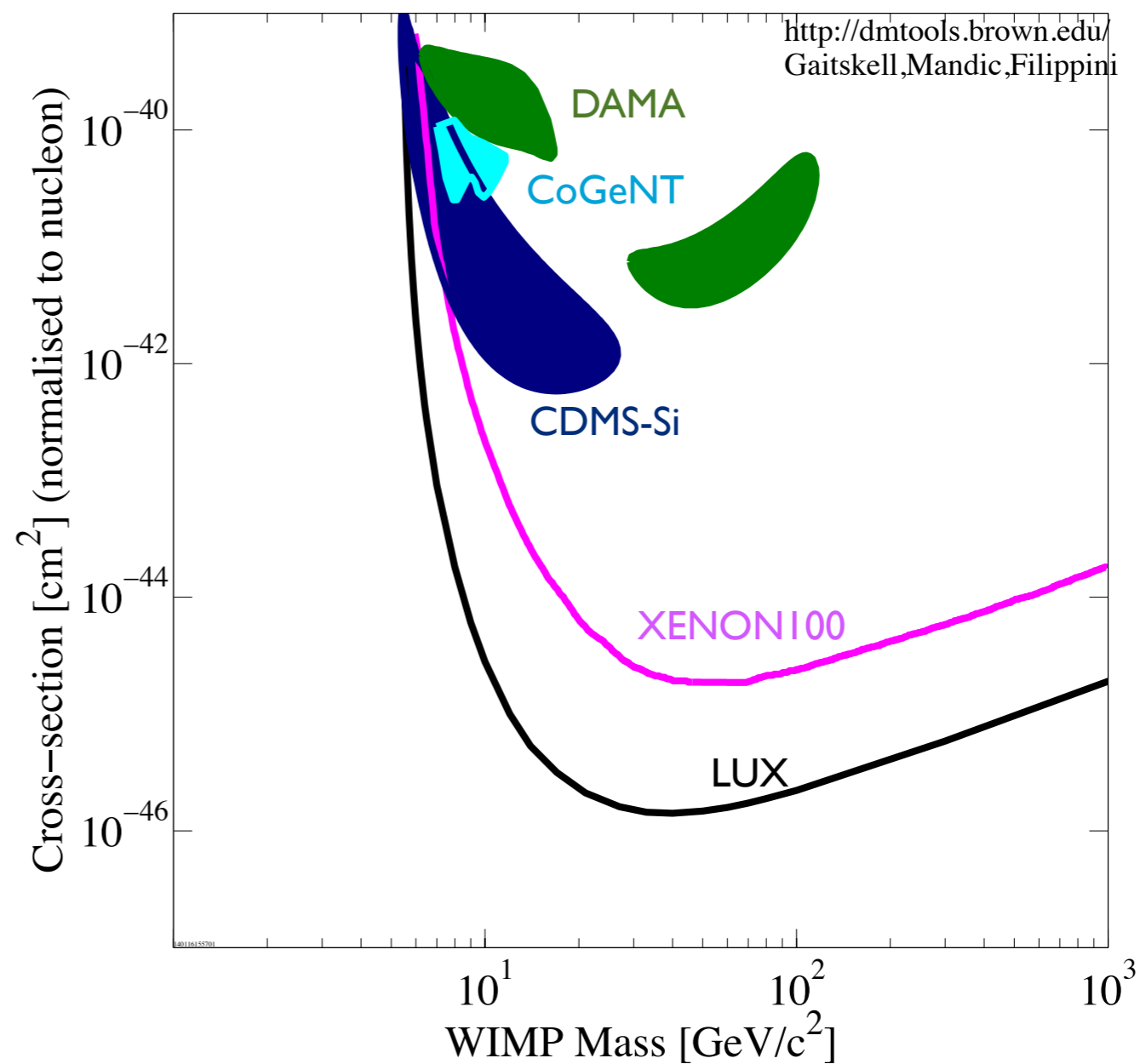
Why Dark Matter?



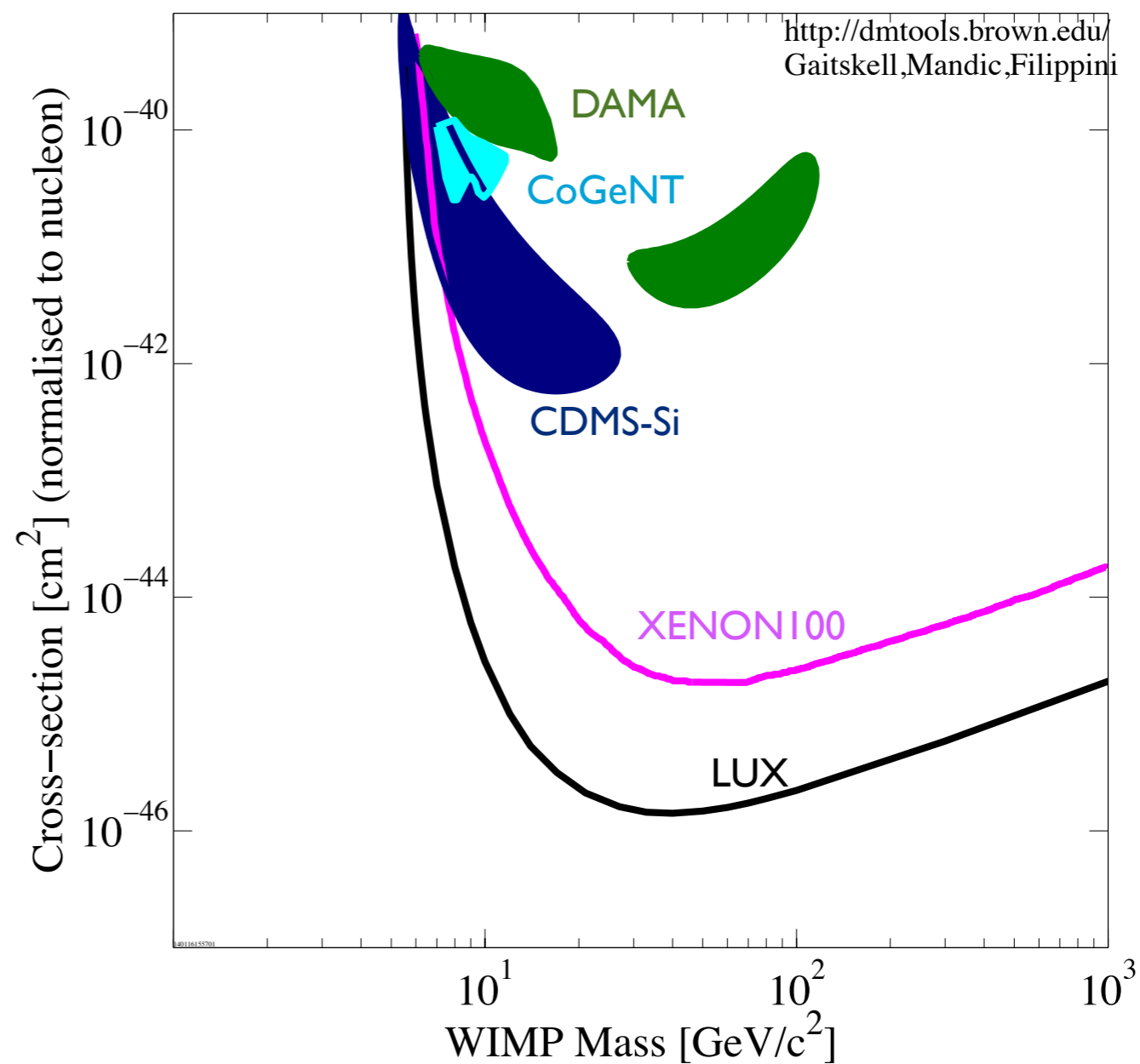
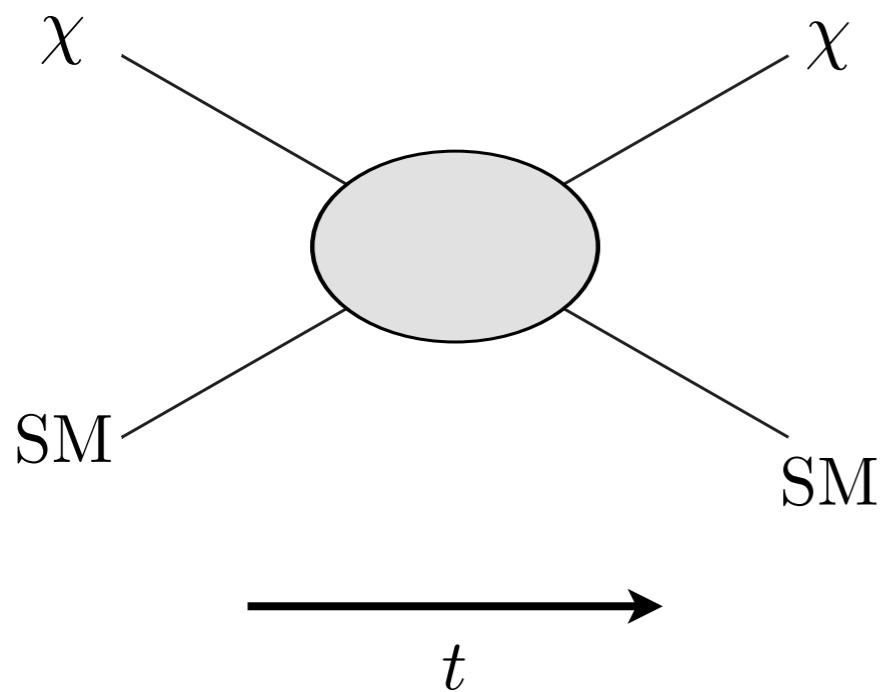
$$\Omega_d \sim 0.2$$

$$\Omega_b \sim 0.04$$

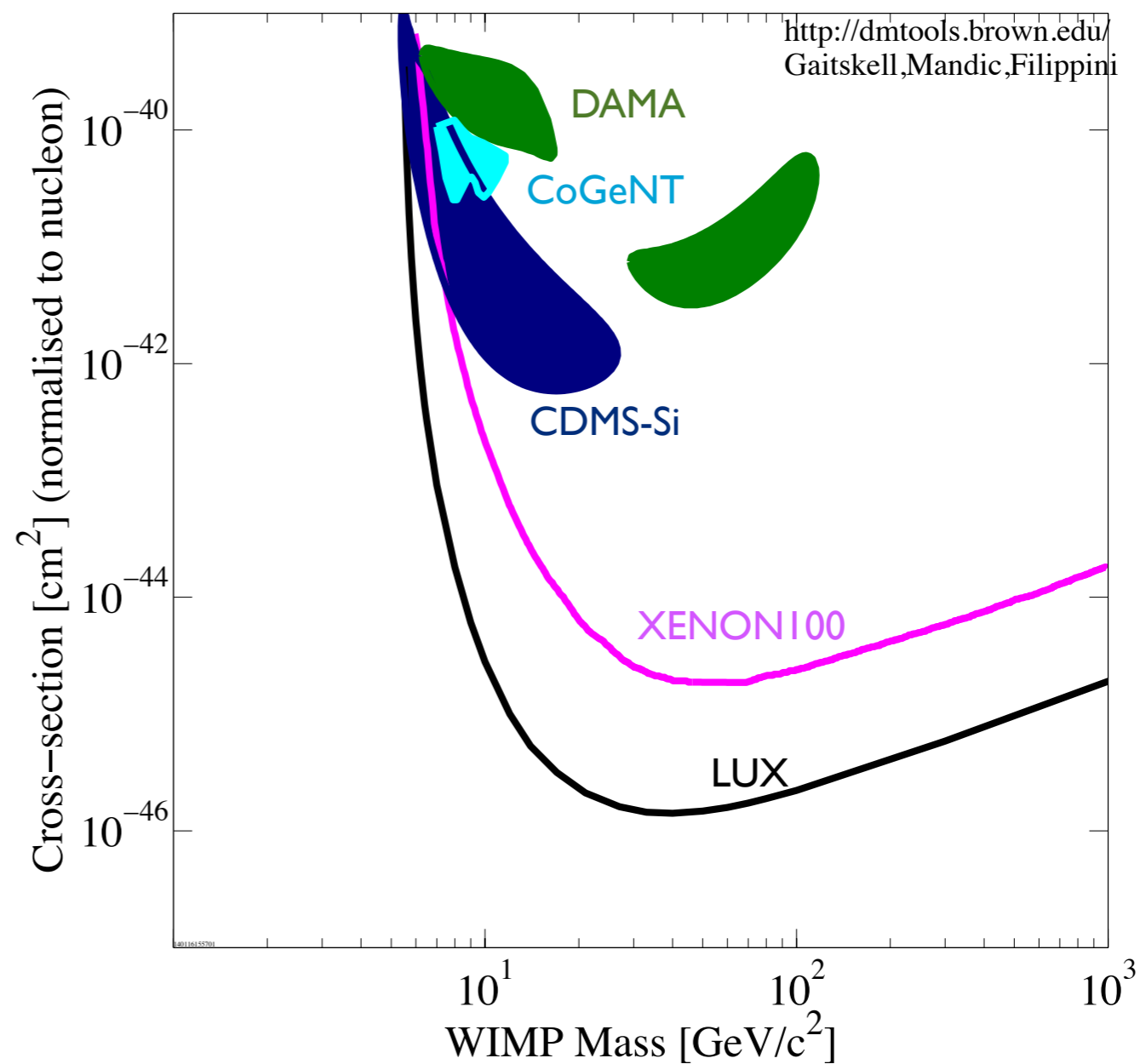
Direct Detection



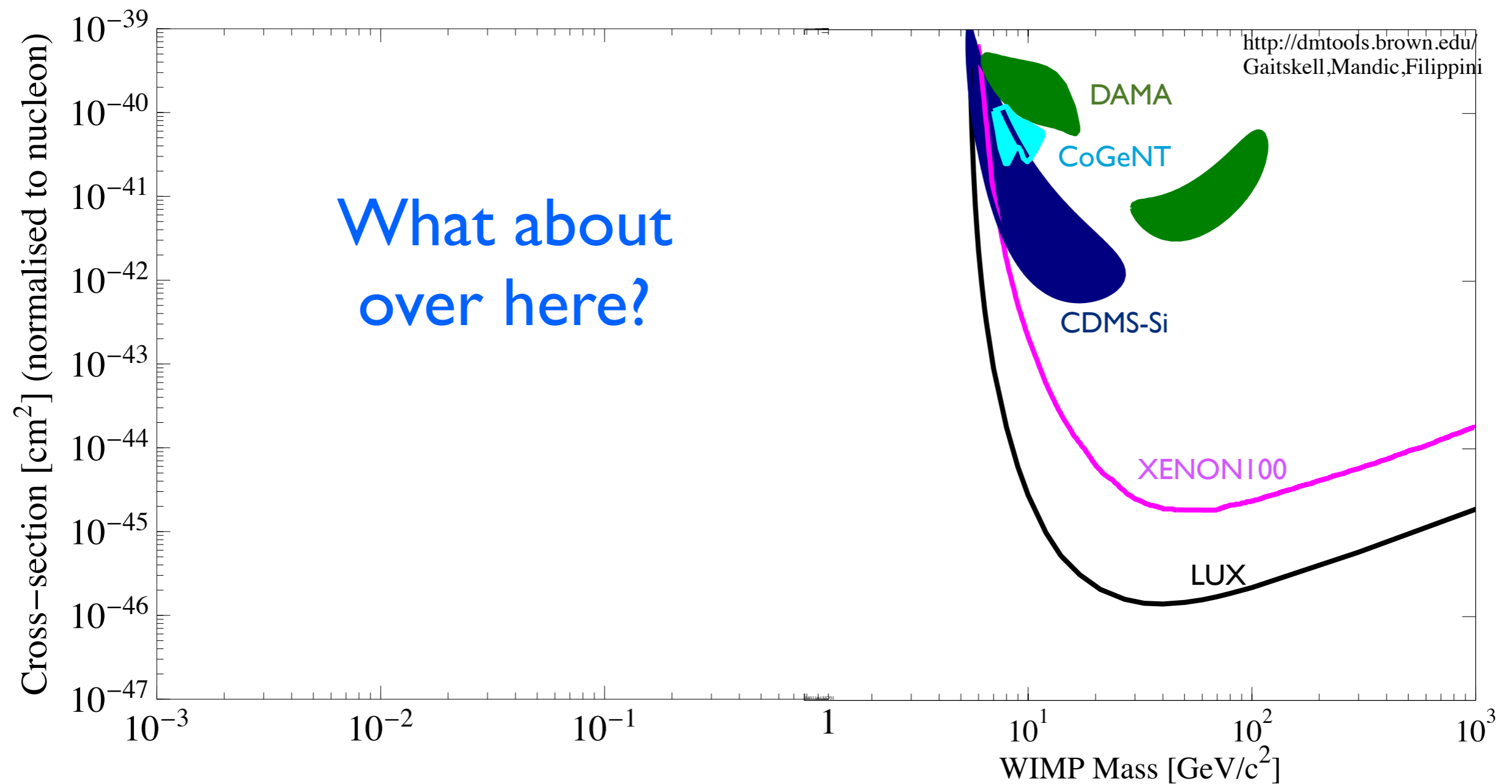
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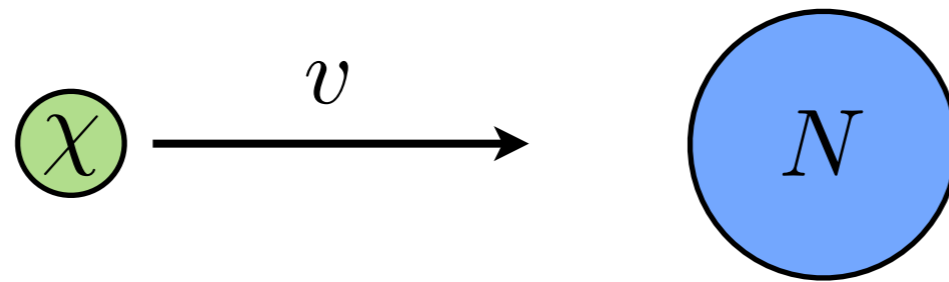
Direct Detection



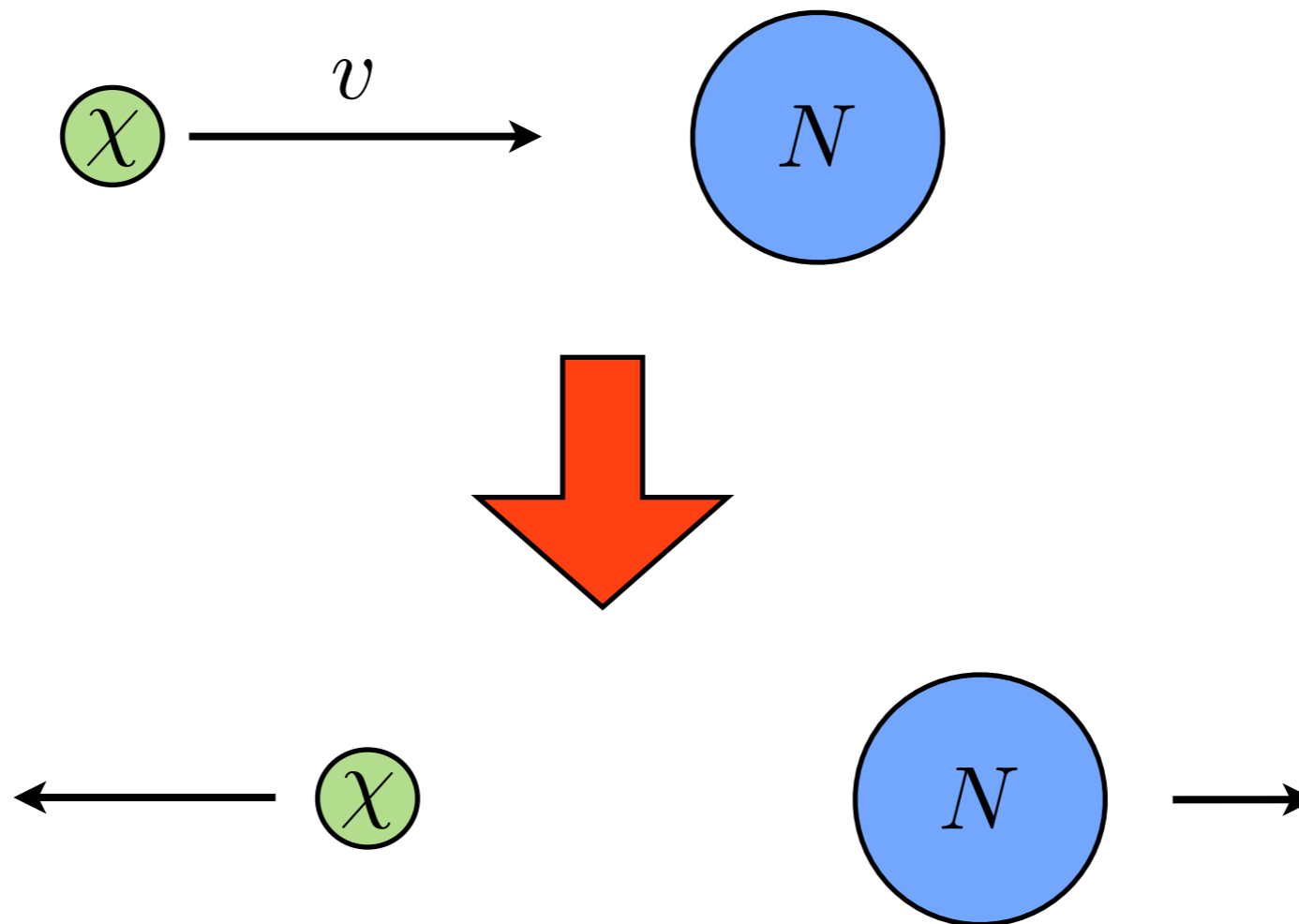
Direct Detection



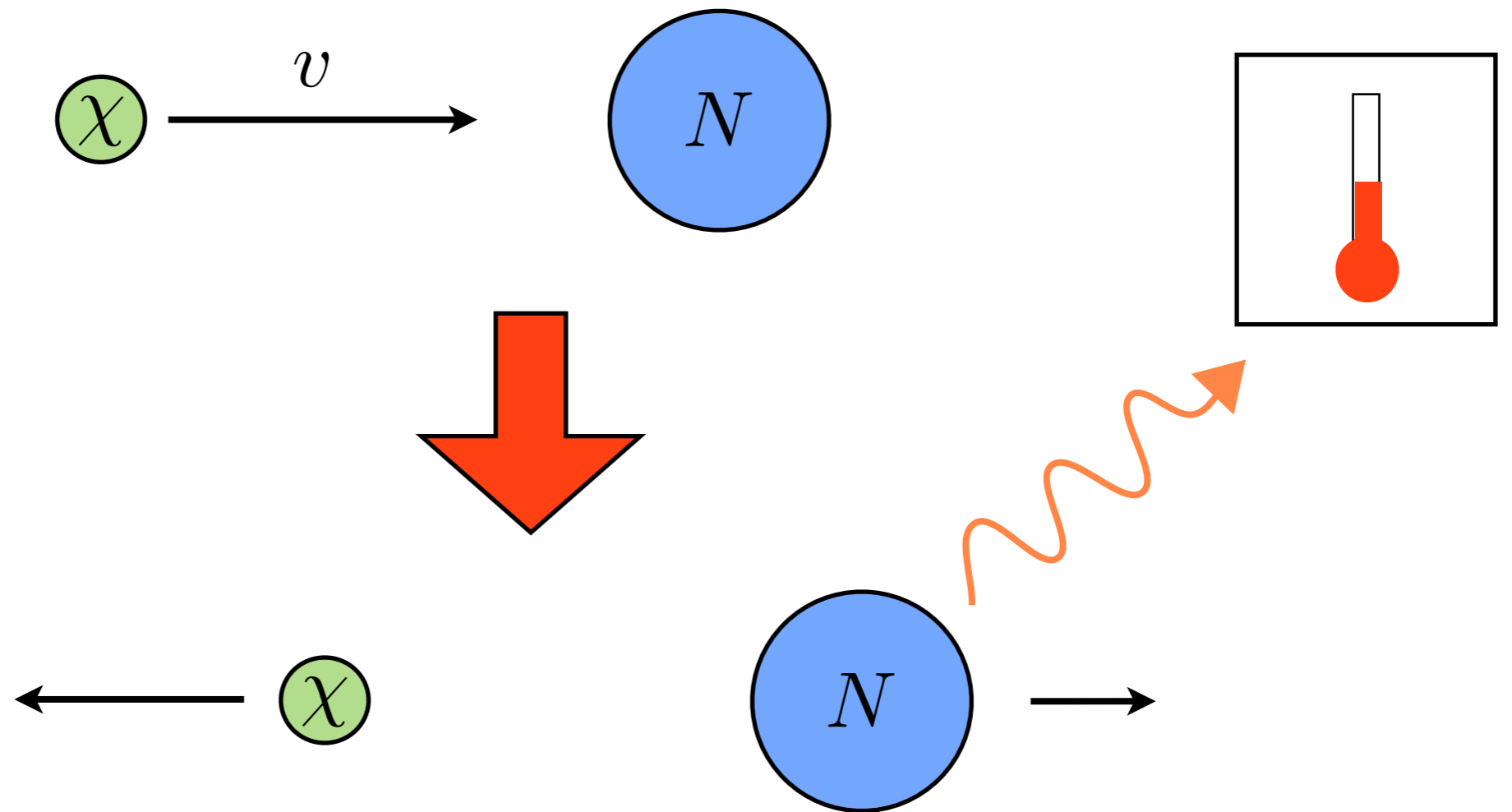
Direct Detection



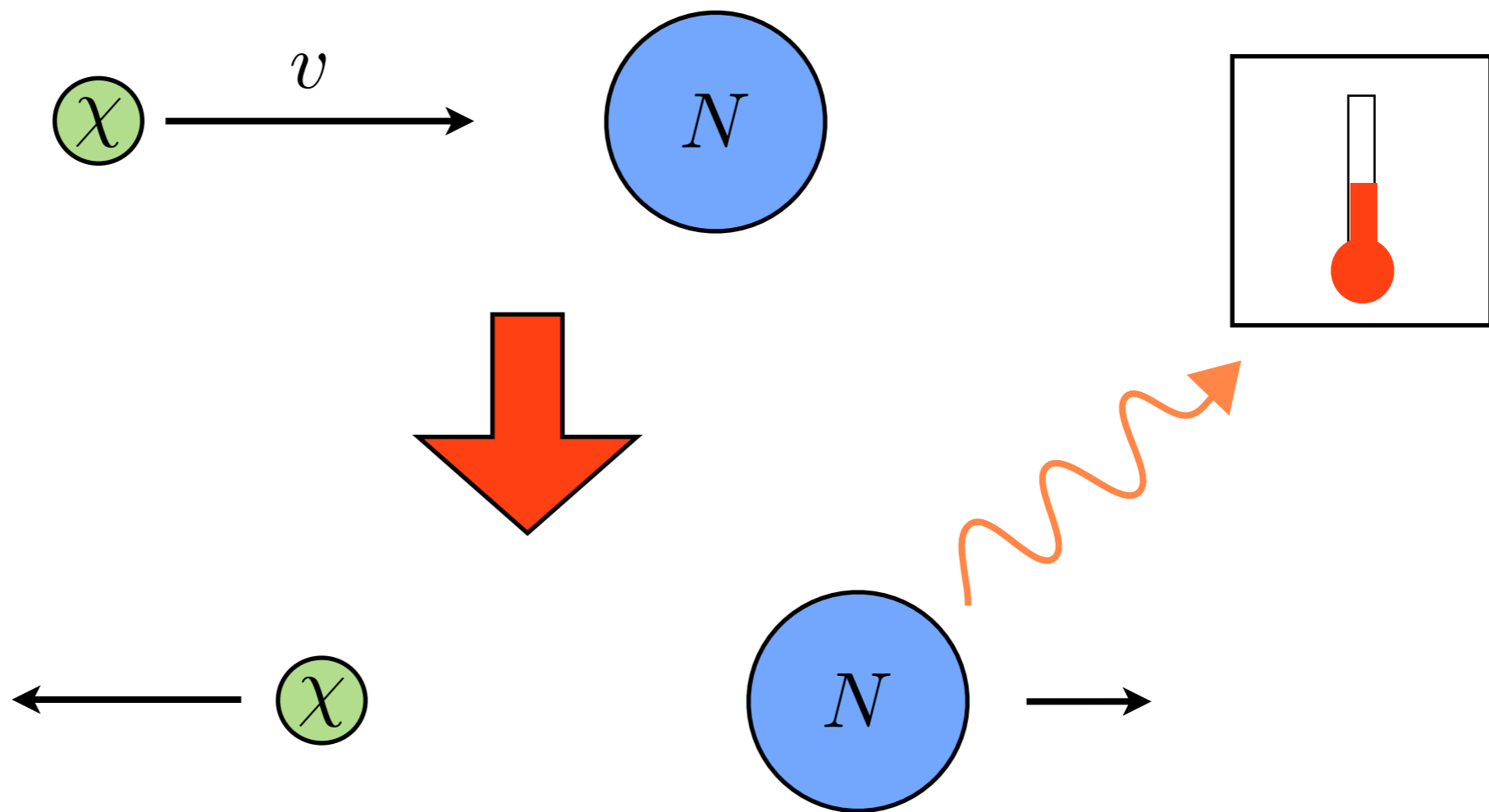
Direct Detection



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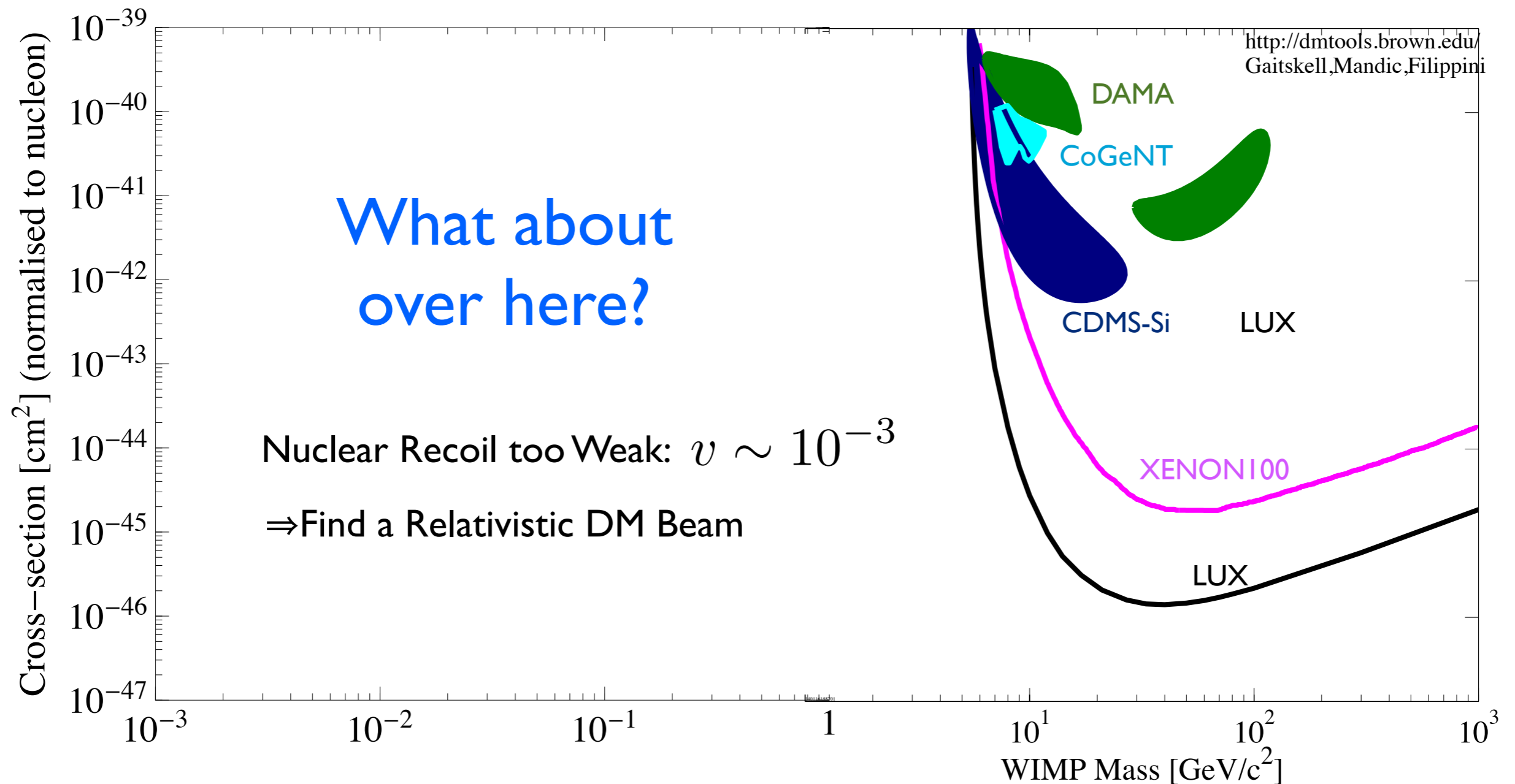


Direct Detection

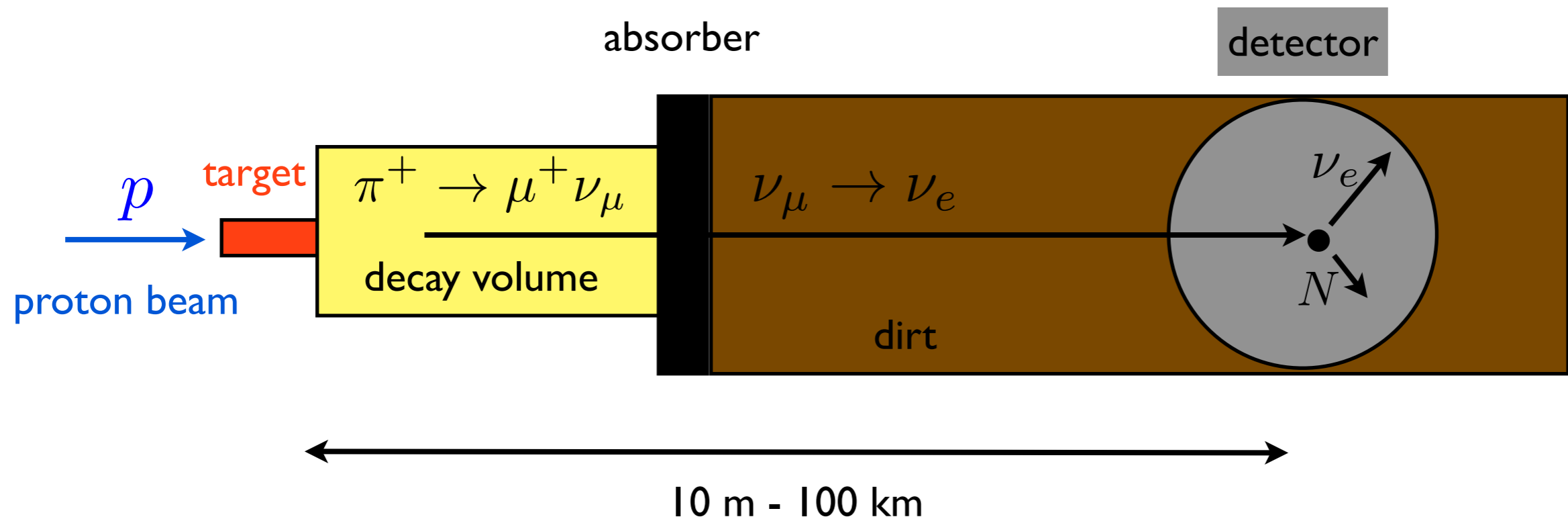


$$E_R \leq \frac{2\mu^2 v^2}{m_N} \rightarrow \frac{2m_\chi^2 v^2}{m_N} \simeq 20 \text{ eV} \left(\frac{m_\chi}{100 \text{ MeV}} \right)^2 \left(\frac{v}{10^{-3}} \right)^2$$

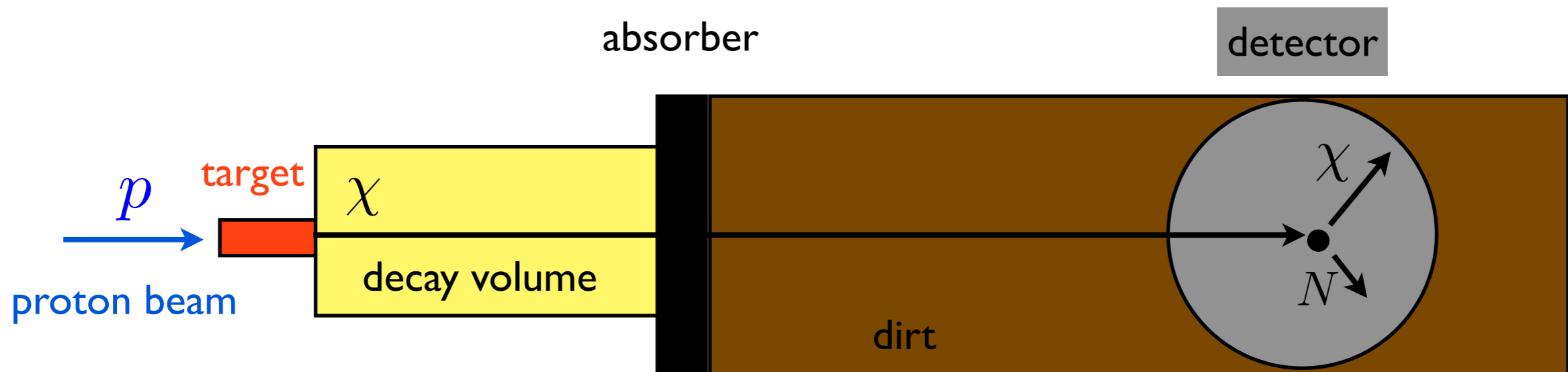
Direct Detection



Neutrino Factories

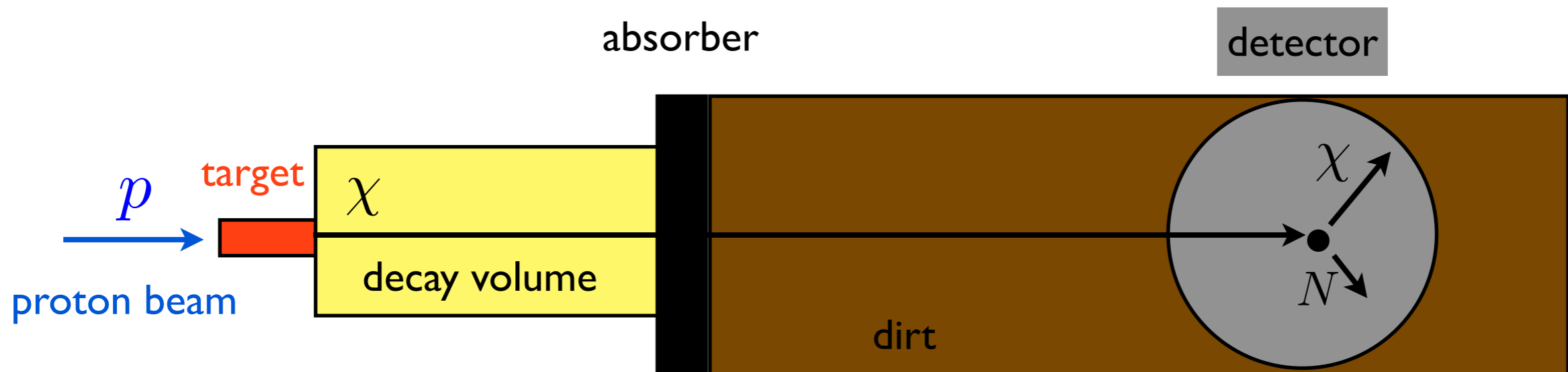


Dark Matter Factories



[Batell, Pospelov, Ritz '09]

Dark Matter Factories



MiniBooNE, MINOS, MicroBooNE,
NOvA, T2K, LBNE, Project X, ...

Neutrino Factories

Experiment	Beam Energy (E_{CM})	Near Detector Dist.	POT
Booster/ MiniBooNE	8.9 GeV (4.2 GeV)	540 m	1.8×10^{21}
NuMi/MINOS	120 GeV (15.5 GeV)	970 m	1.6×10^{21}
J-Parc Main Ring/ T2K	30 GeV (7.7 GeV)	280 m	3.0×10^{20}
CNGS/OPERA, ICARUS	400 GeV (28 GeV)	n/a	1.7×10^{20}

$$\int \mathcal{L} dt \sim 10^6 \text{ fb}^{-1} \left(\frac{N_{\text{POT}}}{10^{20}} \right) \left(\frac{n_{\text{targ.}}}{10^{23} \text{ cm}^{-3}} \right) \left(\frac{L_{\text{targ.}}}{100 \text{ cm}} \right)$$

Why Light Dark Matter?

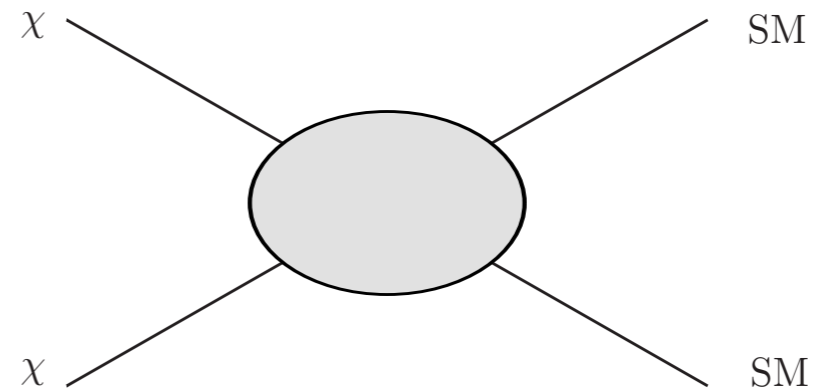
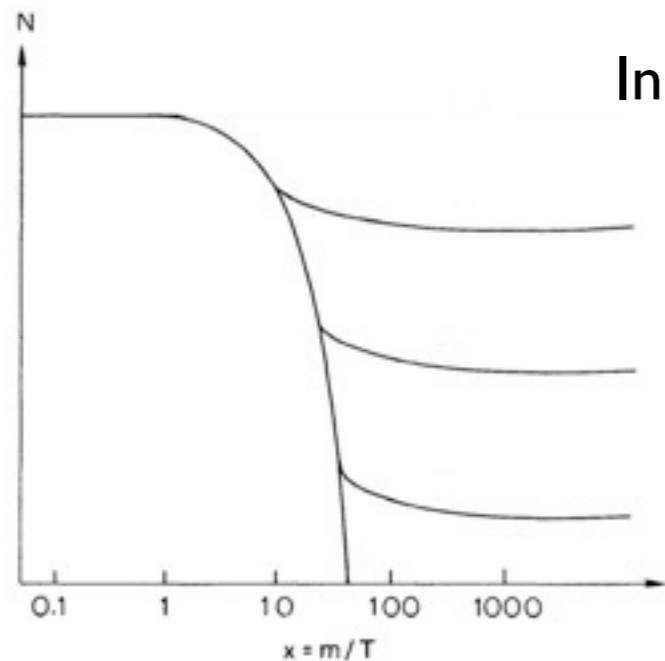
- Dark matter is **empirical** evidence of BSM physics
- Its mass is not well-constrained
- Weak-scale DM has (rightfully) gotten lots of attention
 - Weak-scale, masses, couplings \Rightarrow correct abundance
 - Good candidates in models designed to understand the weak scale
 - Huge experimental effort (direct detection, LHC, ...)
- So far not too much new physics at the LHC...
- Maybe dark matter is not connected to the weak scale, or could be part of a complicated sector with a number of scales (like the visible sector is)

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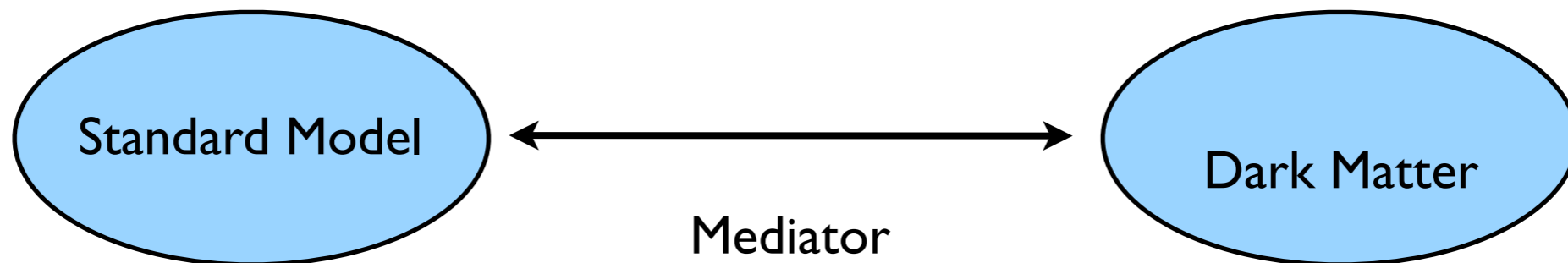
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\Rightarrow We must look everywhere we can for DM!

Thermal Relics

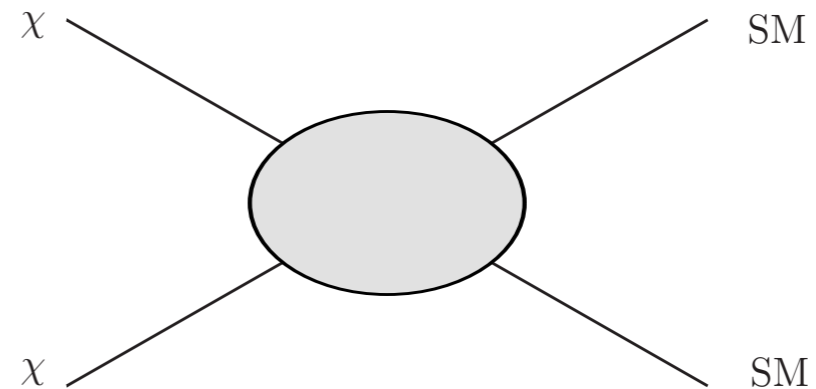
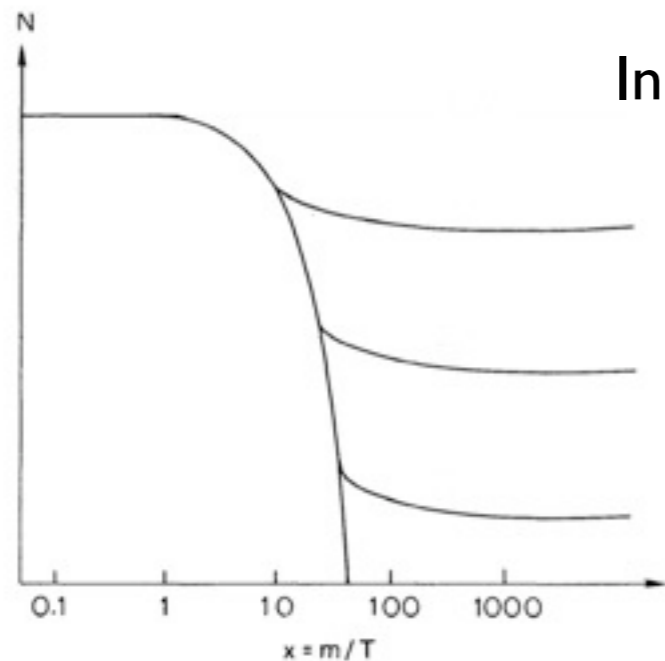


$$\sigma \propto \frac{g^4 m_\chi^2}{M^4} \sim \mathcal{O}(\text{pb})$$

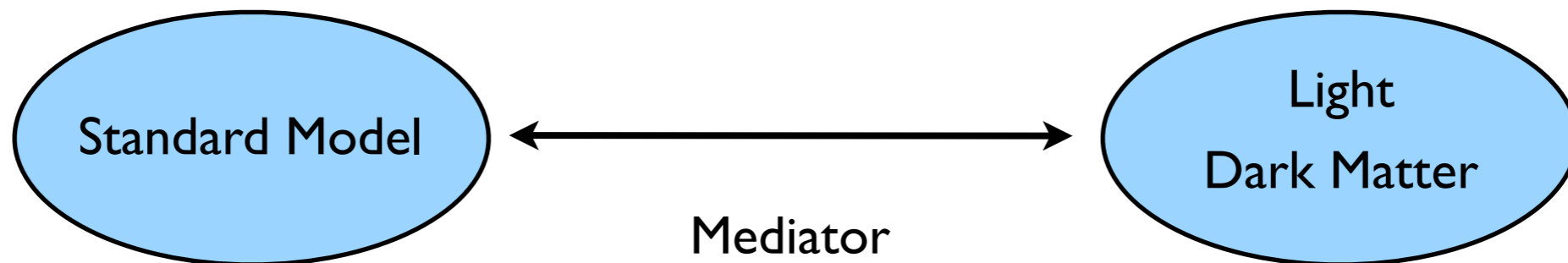


Lee-Weinberg Bound: SM (W, Z, h, ...) mediator $\Rightarrow m_\chi \gtrsim \text{few} \times \text{GeV}$

Thermal Relics

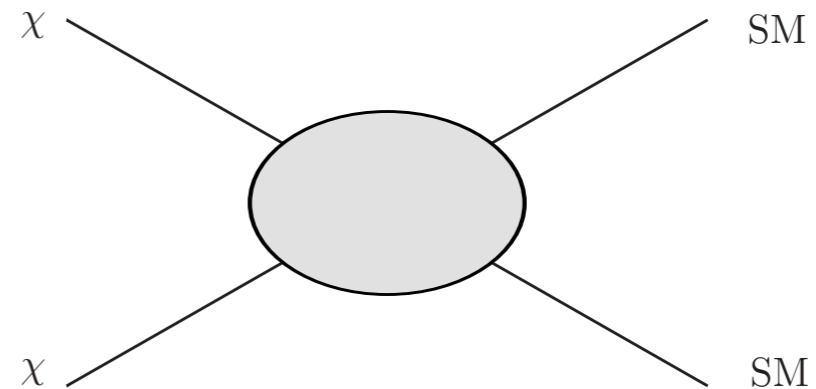
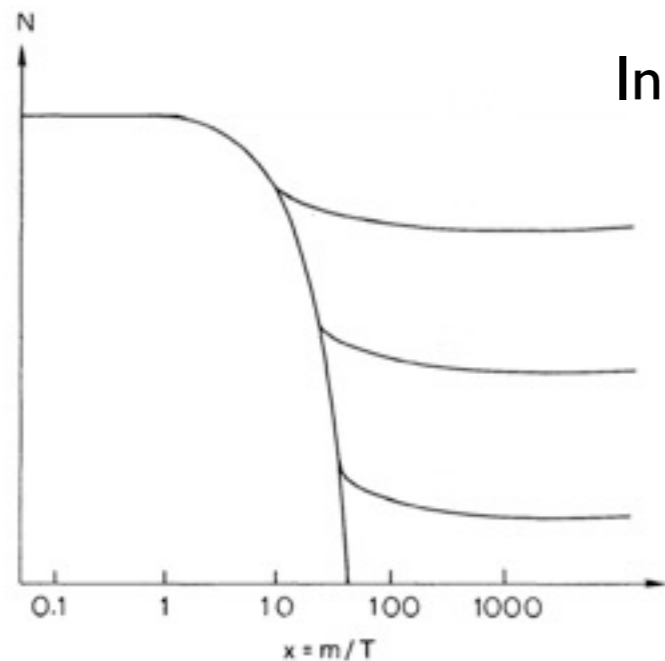


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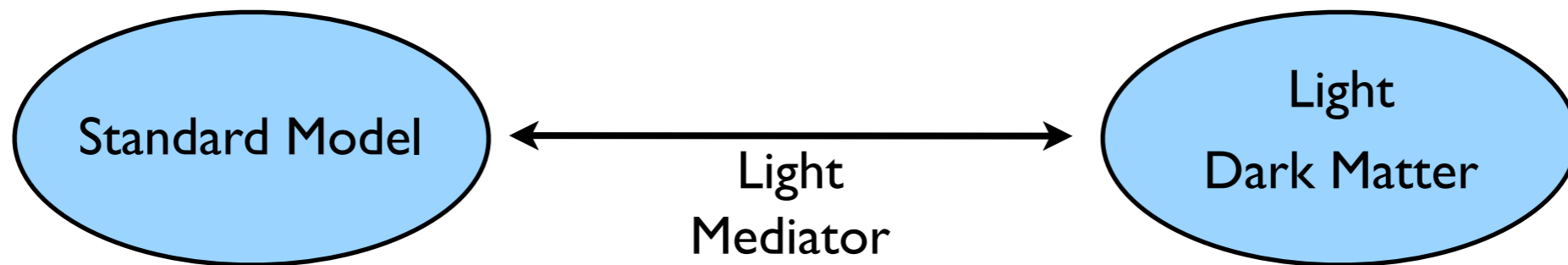


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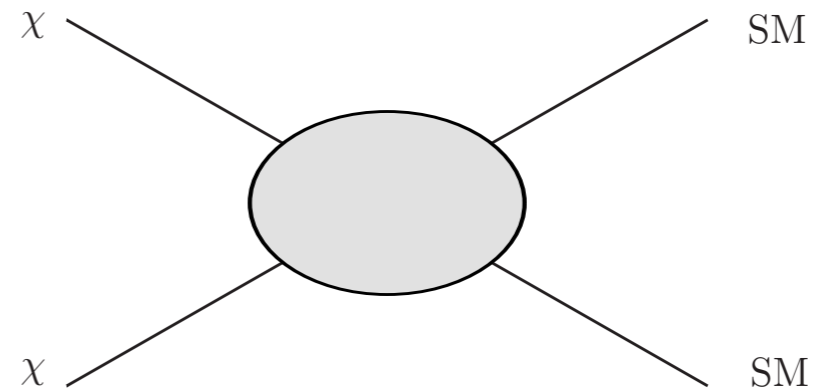
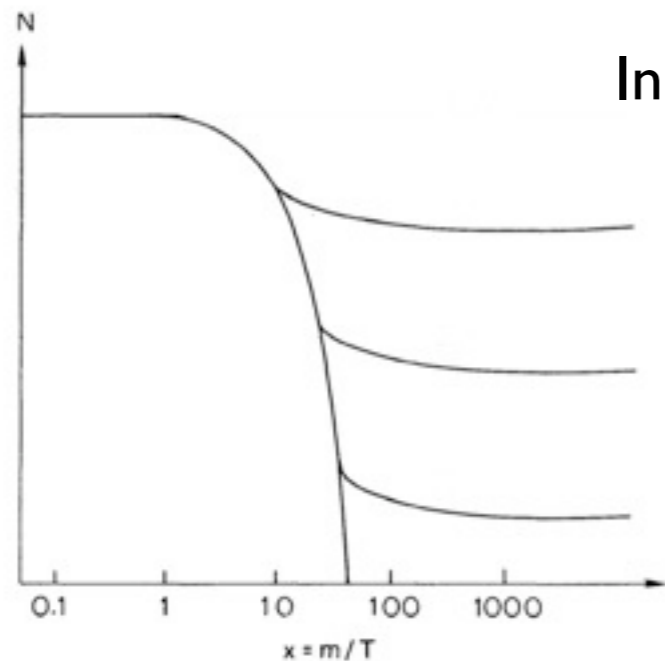


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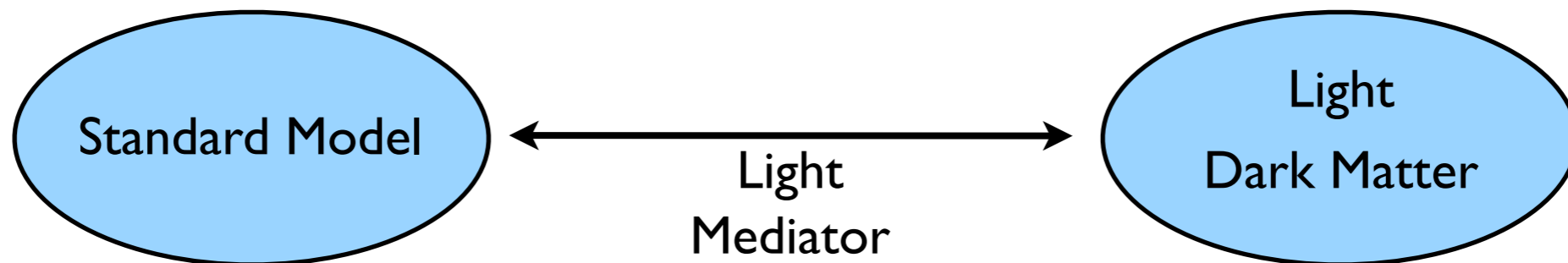


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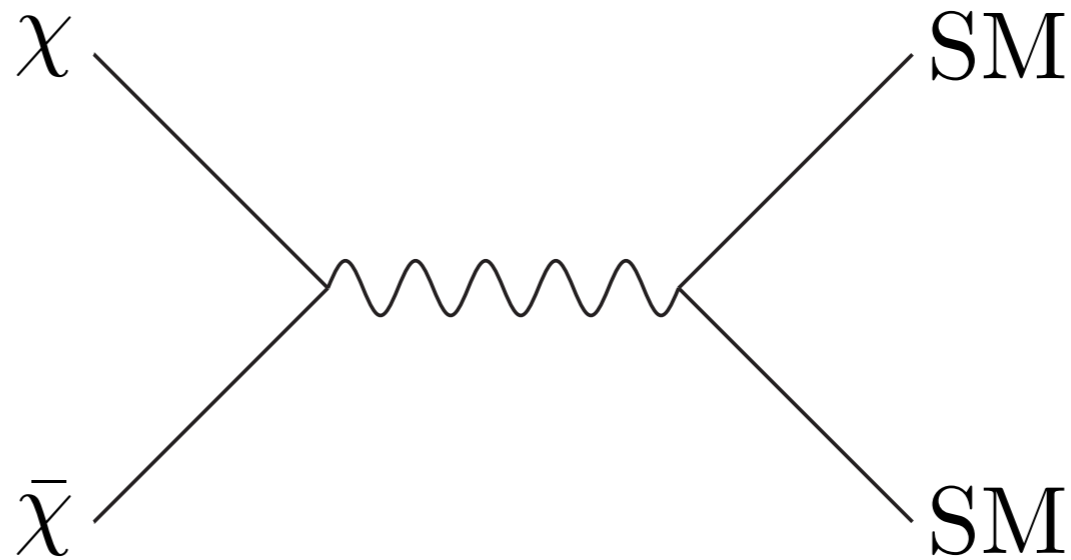


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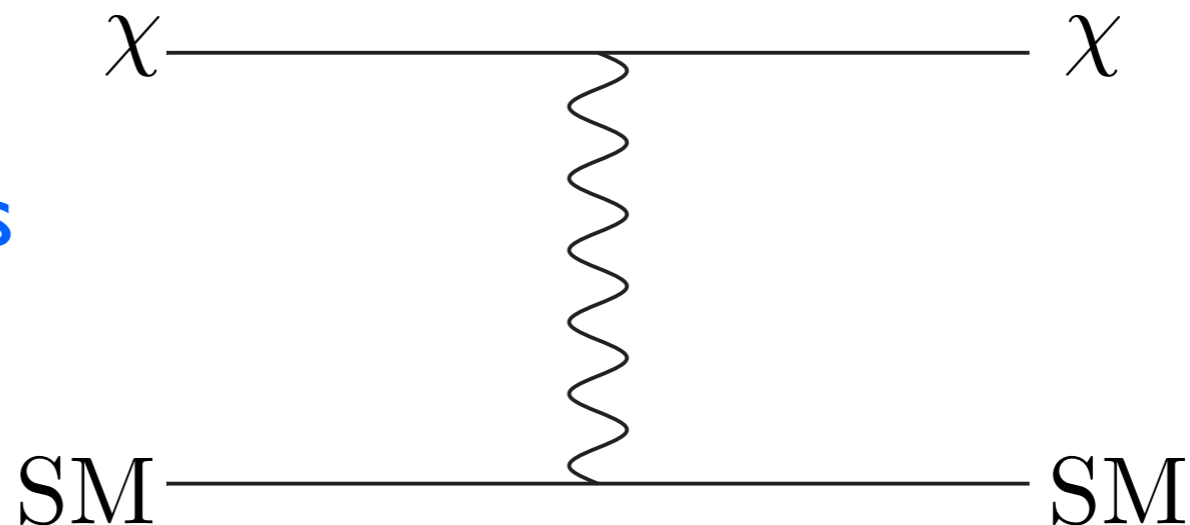
Light Mediator \Rightarrow Probed at Low Energy

Mediators Do Double Duty

Open annihilation
channels for DM
 \Rightarrow viable thermal relic
[Boehm, Fayet '03]



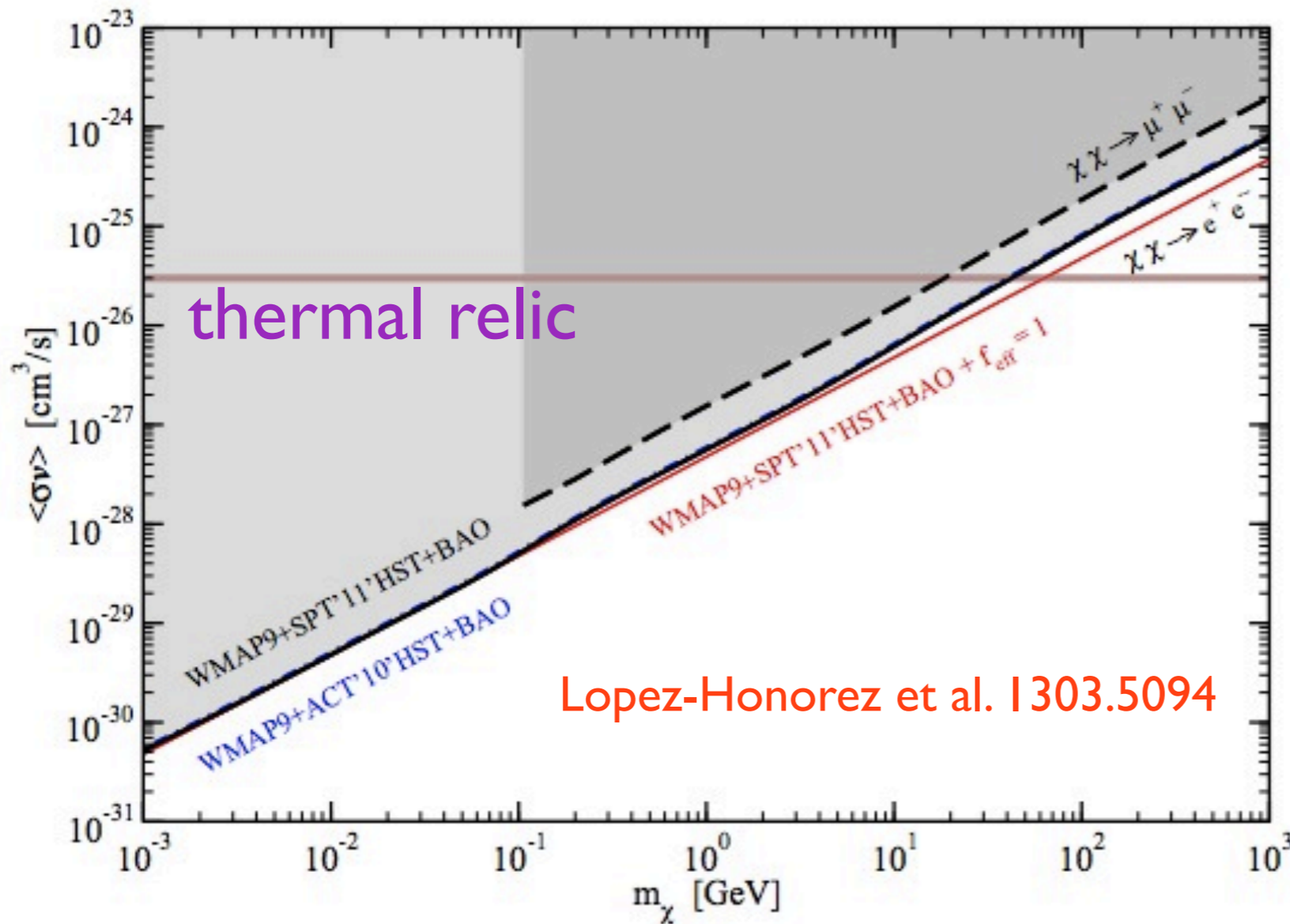
Mediate interactions
with SM



Probes of Light DM/Mediators

- CMB [Padmanabhan, Finkbeiner, Slatyer, Galli, Lin]
- X rays, Gamma rays [Essig, Kuflik, McDermott, Volansky, Zurek]
- BBN [Serpico, Raffelt; Pospelov, Pradler]
- DM self-interaction [Tulin, Yu, Zurek]
- Supernova, star cooling [Dreiner, Fortin, Hanhart, Ubaldi]
- Monojets [FNAL, Irvine, LANL, ...]
- Meson decays $\pi^0 \rightarrow \gamma + \text{inv.}$ $K^+ \rightarrow \pi^+ + \text{inv.}$ $J/\psi \rightarrow \text{inv.}$
- Precision QED [Fayet, Pospelov]
- e^+e^- , monophotons [Essig, Mardon et al.; Izaguirre, Krnjaic et al., BaBar, ...]
- Direct Detection (scattering on electrons) [Essig, Mardon, Volansky]

CMB Constraints



[Padmanabhan, Finkbeiner]

[Slatyer, Padmanabhan, Finkbeiner]

[Finkbeiner, Galli, Lin, Slatyer]

DM annihilation at $z=10-1000$ can affect recombination as encoded in CMB anisotropy measurements

s-wave annihilation severely restricted
p-wave OK ($T \sim 0.1$ eV)

A Benchmark Model

Add scalar DM and a vector mediator:

$$\mathcal{L} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 + g_B V_\mu J_B^\mu - \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu} + \dots$$

with the covariant derivative given by

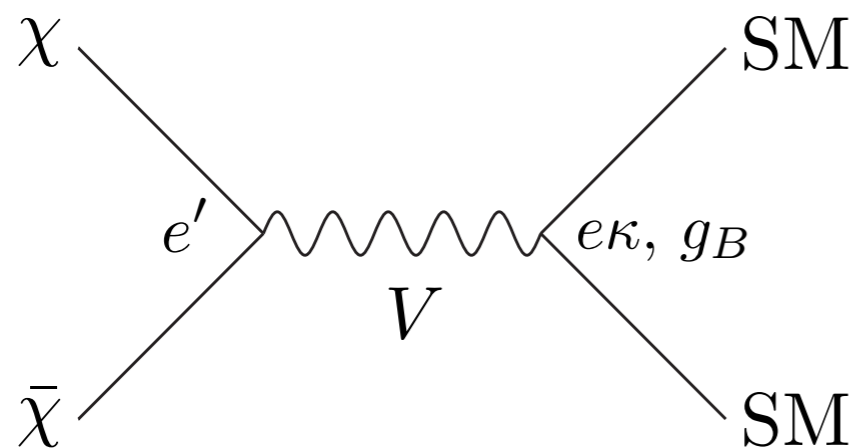
$$D_\mu = \partial_\mu - ig_B q_B V_\mu \equiv \partial_\mu - ie' V_\mu$$

In the physical basis the interaction of the vector with the SM is

$$V_\mu (g_B J_B^\mu - \kappa e J_{\text{em}}^\mu)$$

$$J_B^\mu = \frac{1}{3} \sum_q \bar{q} \gamma^\mu q$$

$$J_{\text{em}}^\mu = \sum_f q_f \bar{f} \gamma^\mu f$$



5 new params. $m_\chi, m_V, \kappa, g_B, e'$

- can obtain relic abundance
- scalar DM: p-wave annihilation so CMB okay
- $\kappa \neq 0$ case can address g-2 anomaly

- baryonic vector is ideally suited for proton beam experiments
- needs some extension for anomaly cancelation, sub-GeV DM annihilation

← [Batell, deNiverville, DM, Pospelov, Ritz, in progress]

[Dobrescu et al. 1404.3947]

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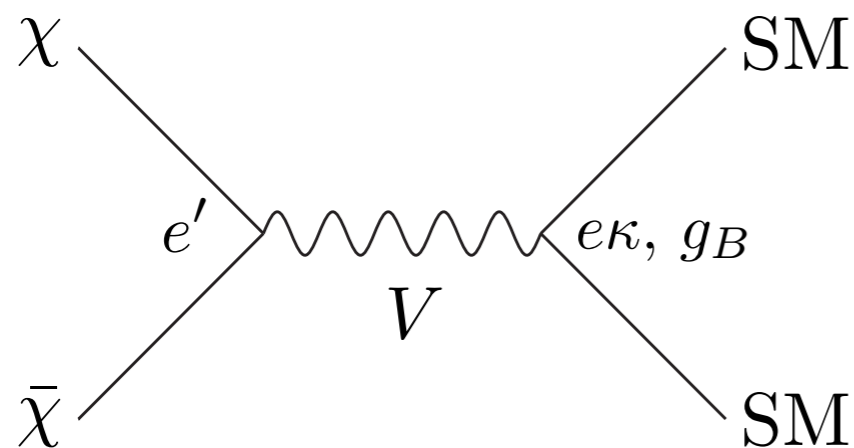
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$$A', Z', Z_d, \gamma_d, \epsilon$$



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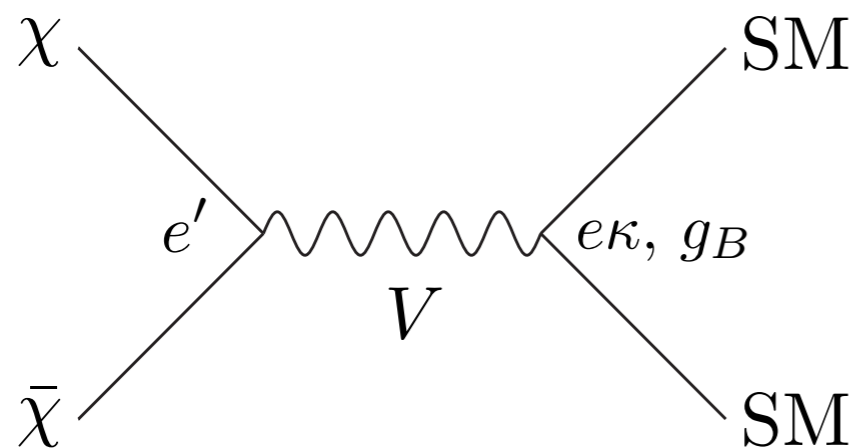
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No!
 ~~$A', Z', Z_d, \gamma_d, \epsilon$~~



5 new params. $m_\chi, m_V, \kappa, g_B, e'$

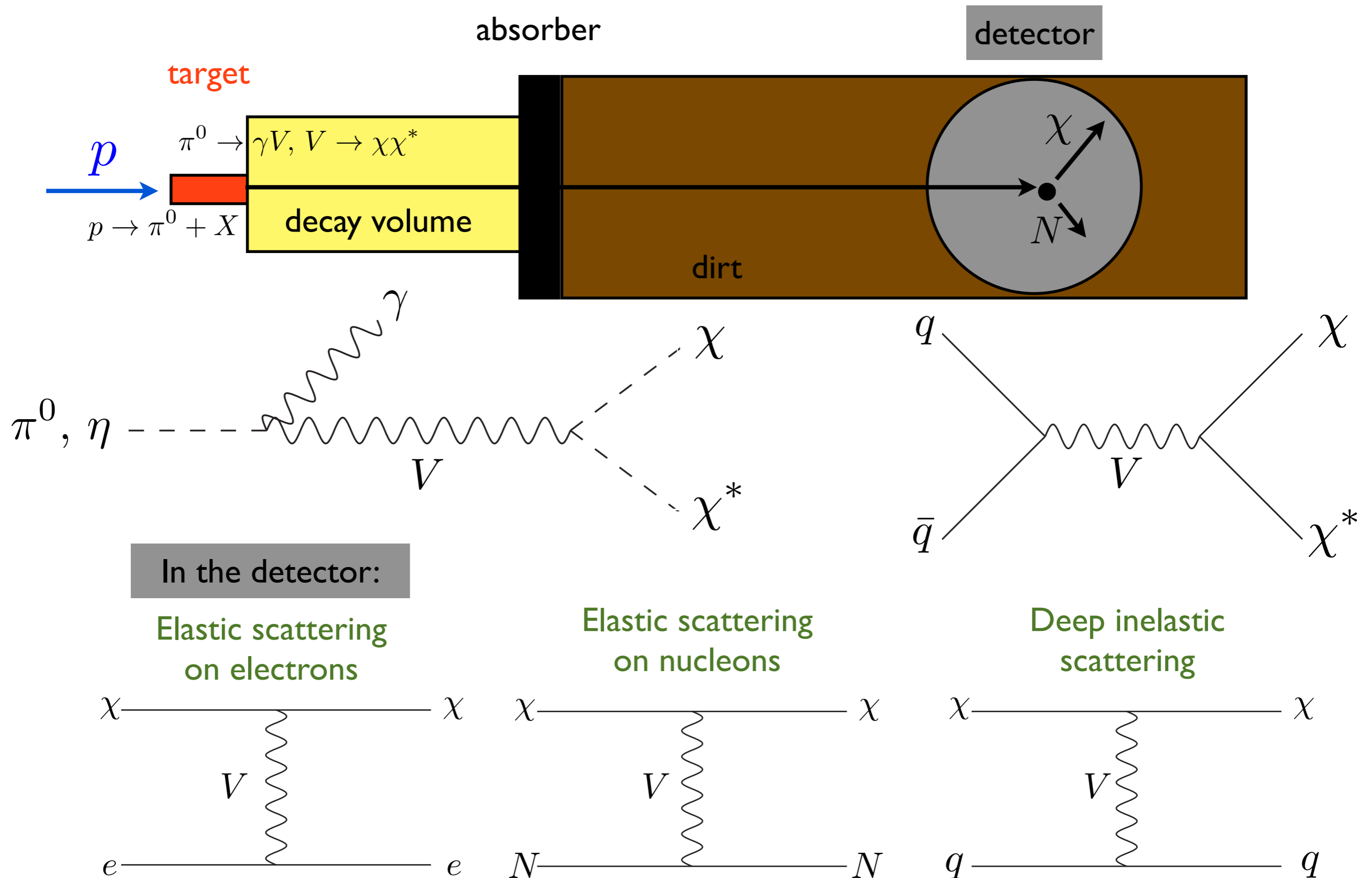
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[Dobrescu et al. 1404.3947]

DM Production & Scattering



Rate Estimates

e.g., start with charged pion flux: $N_{\pi^+} = \frac{\Phi_\nu A_{\text{det}}}{\gamma^2 (d\Omega_{\text{lab}}/4\pi)}$

To estimate the number of neutral pions: $N_{\pi^0} \simeq r_{\text{horn}} \times N_{\pi^+}$

since horn does not focus the neutral particles

The number of DM particles produced through π^0 decays is

$$N_{\chi, \text{prod}} = N_{\pi^0} \times \text{Br}_{\pi^0 \rightarrow \gamma V}$$

and the number that reach the detector is $N_\chi = N_{\chi, \text{prod}} \gamma^2 \frac{d\Omega_{\text{lab}}}{4\pi}$

The neutral current scattering cross section is given by

$$\frac{d\sigma_{\chi N \rightarrow \chi N}^V}{dE_\chi} = \alpha' \left(\frac{g_B}{e} - \kappa \right)^2 \times \frac{4\pi\alpha [F_{1,N}^2(Q^2)A(E, E_\chi) - \frac{1}{4}F_{2,N}^2(Q^2)B(E, E_\chi) - F_{1,N}(Q^2)F_{2,N}(Q^2)C(E, E_\chi)]}{(m_V^2 + 2m_N(E - E_\chi))^2 (E^2 - m_\chi^2)}$$

plus corrections for scattering on bound/free nucleons

Putting this together:

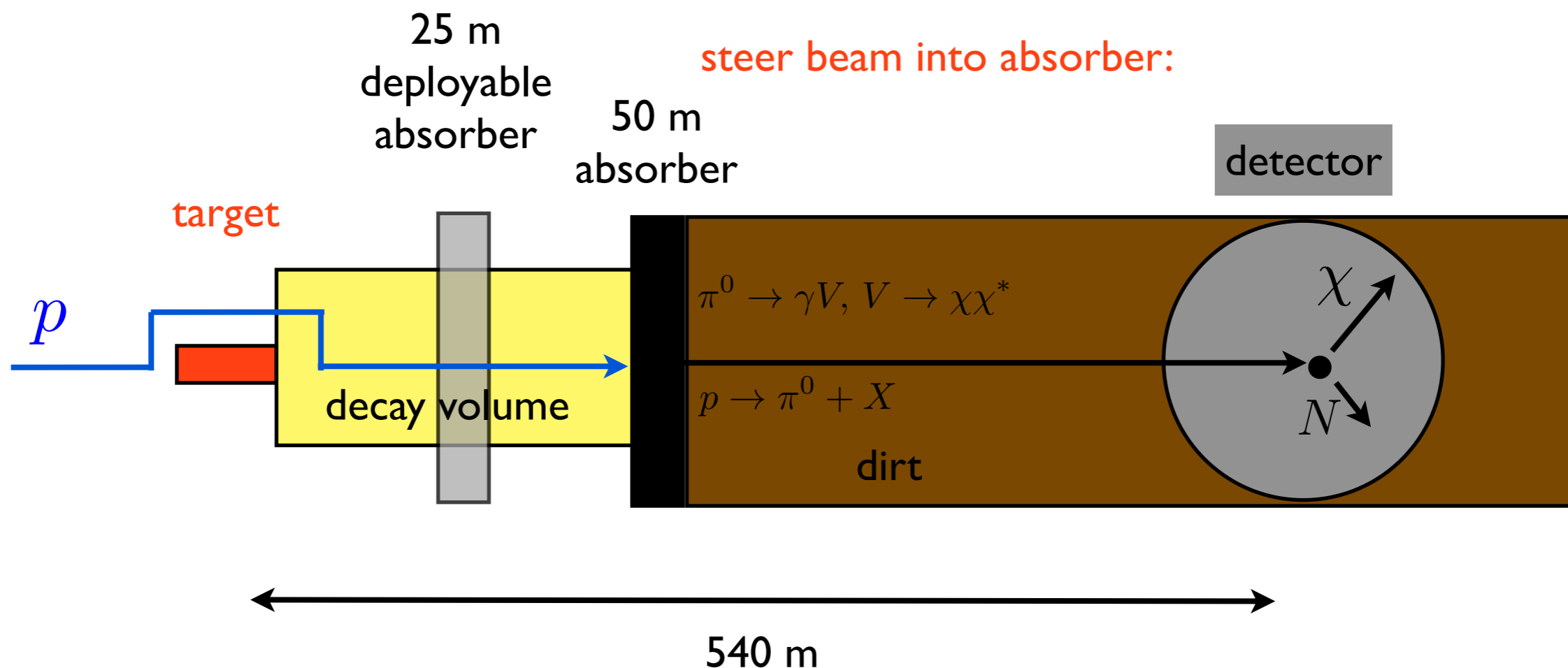
$$N_S \sim 100 \left(\frac{\Phi_\nu}{10^{11} \text{ cm}^{-2}} \right) \left(\frac{r_{\text{horn}}}{1/6} \right) \left(\frac{V_{\text{det}}}{10^9 \text{ cm}^3} \right) \left(\frac{n_N}{10^{23} \text{ cm}^{-3}} \right) \left(\frac{\sigma_{\chi N \rightarrow \chi N}}{10 \text{ pb}} \right) \left(\frac{\text{Br}_{\pi^0 \rightarrow \gamma V}}{10^{-6}} \right)$$

Beating down backgrounds

The signal of DM NC scattering looks very similar to neutrino NC scattering

How can we reduce the neutrino background?

[Focusing on MiniBooNE now for a concrete example (see talk by R. Dharmapalan next for experimental details)]

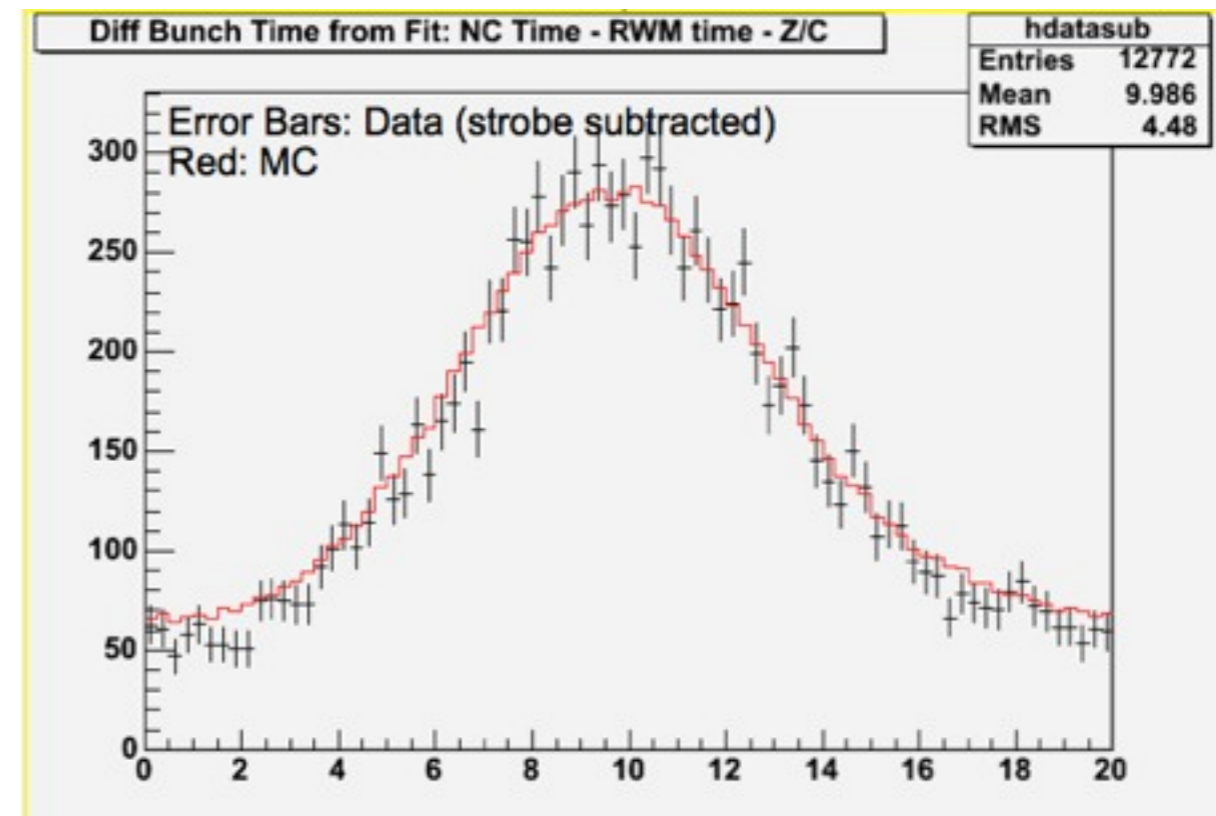
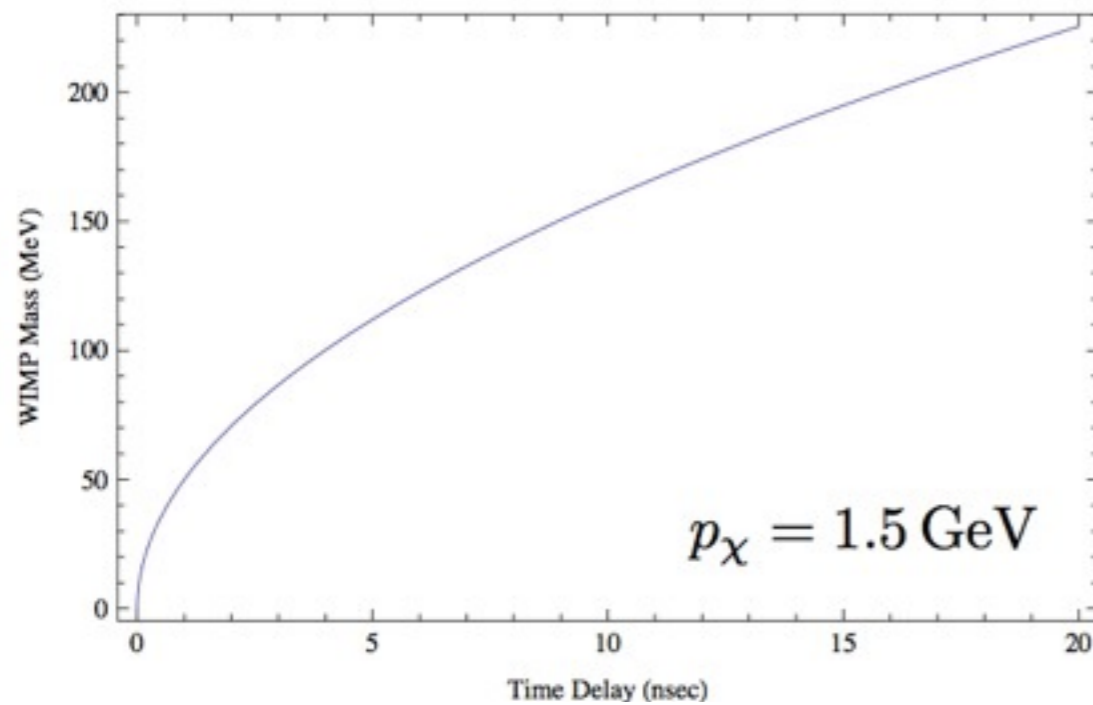


Can reduce neutrino flux by factor of ~ 50

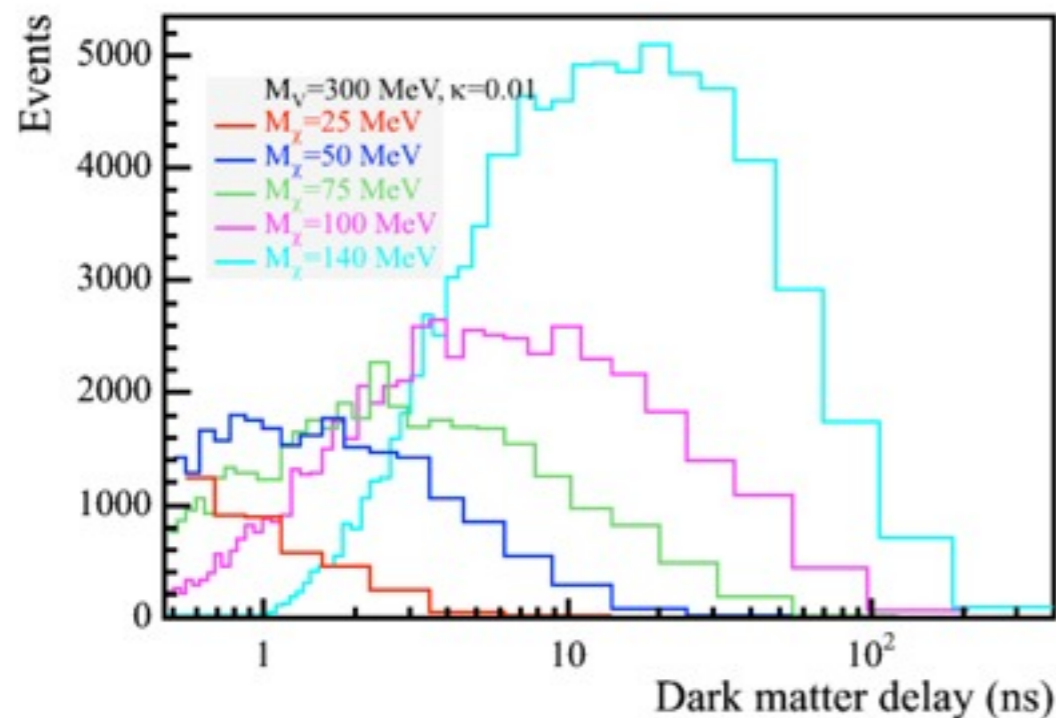
Beating down backgrounds

Timing!

DM is heavier than neutrinos, arrives at detector later



Bunch Timing (nsec)

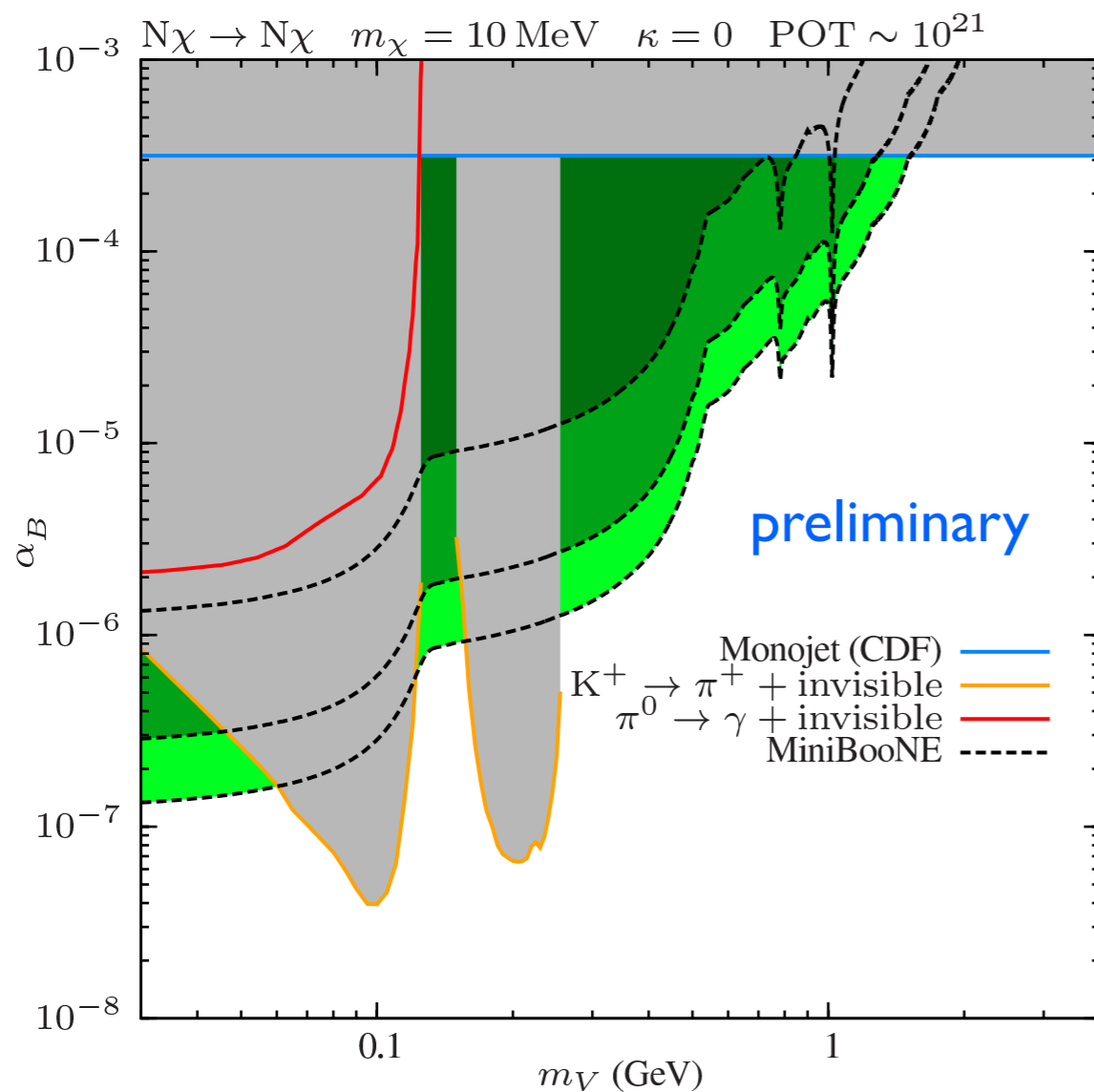


Timing cut (nsec)	Background Reduction (%)	WIMP Velocity β	WIMP Mass (MeV)
3.0	90	0.9984	85
4.6	99	0.9974	108
5.9	99.9	0.9967	122

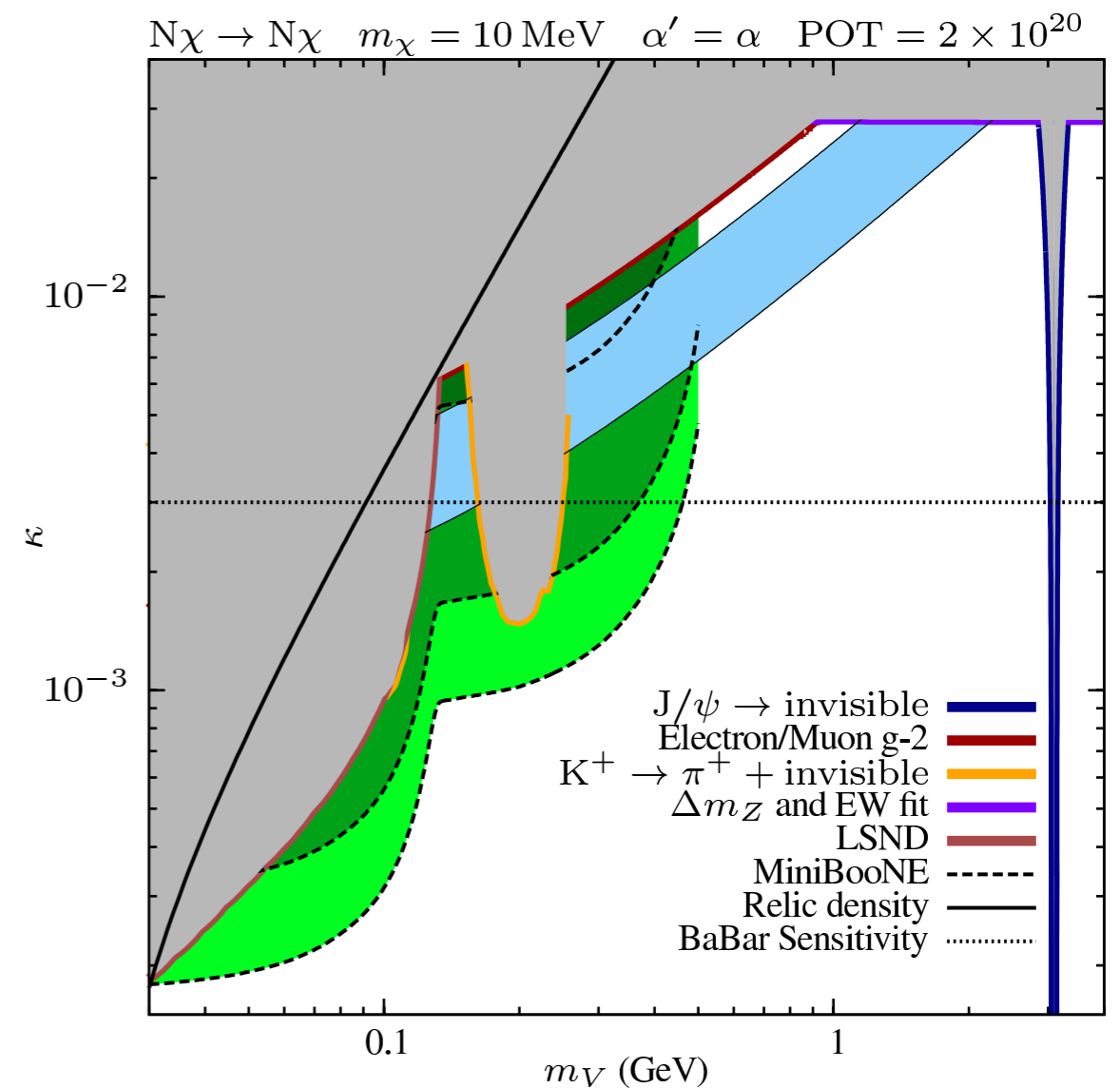
DM signal at MiniBooNE

Dominant production through neutral meson decay
Use Sanford-Wang distribution to estimate

Also use production through vector mesons using VMD
and $q\bar{q}$ -initiated production at higher V masses



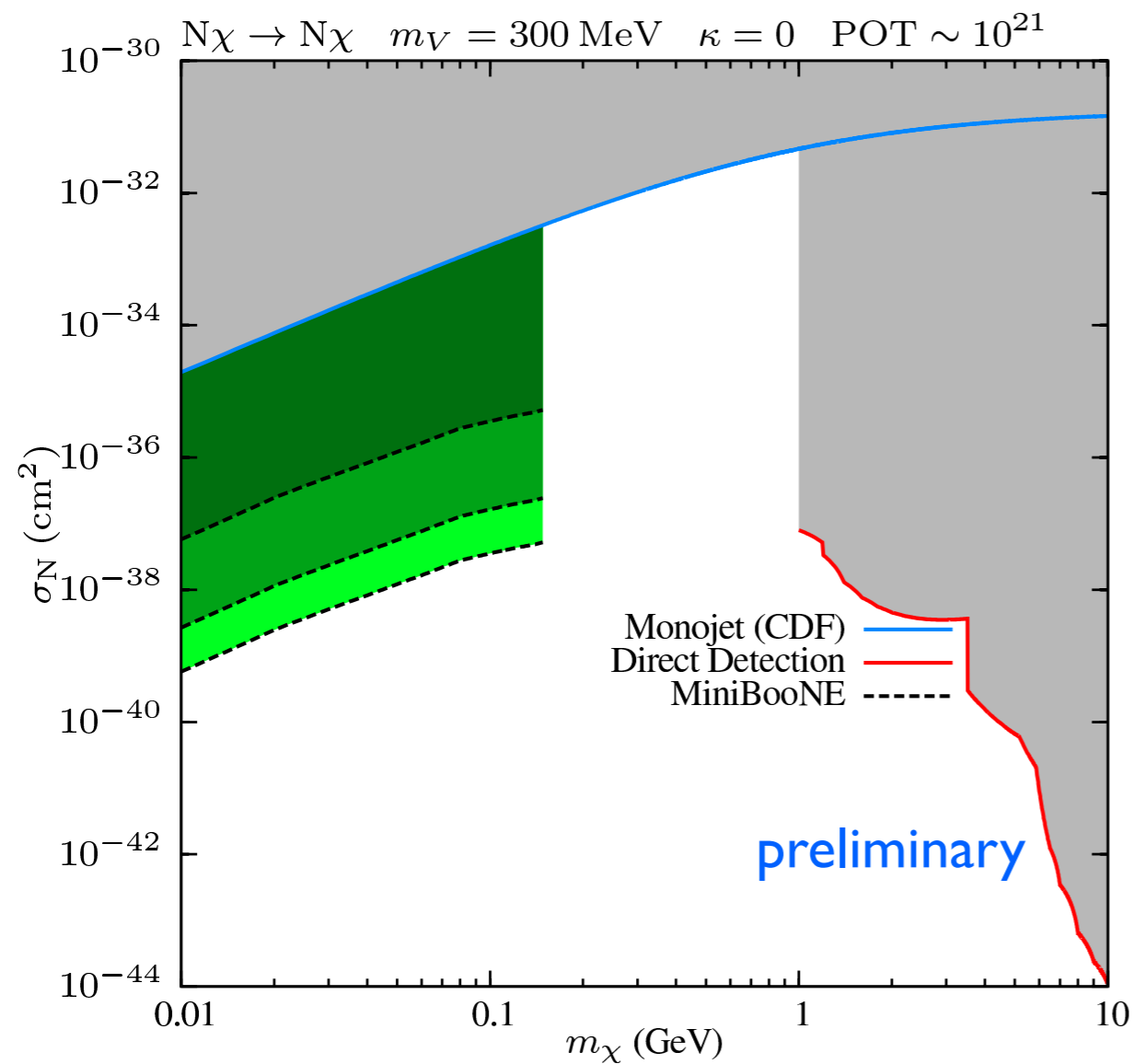
baryonic V



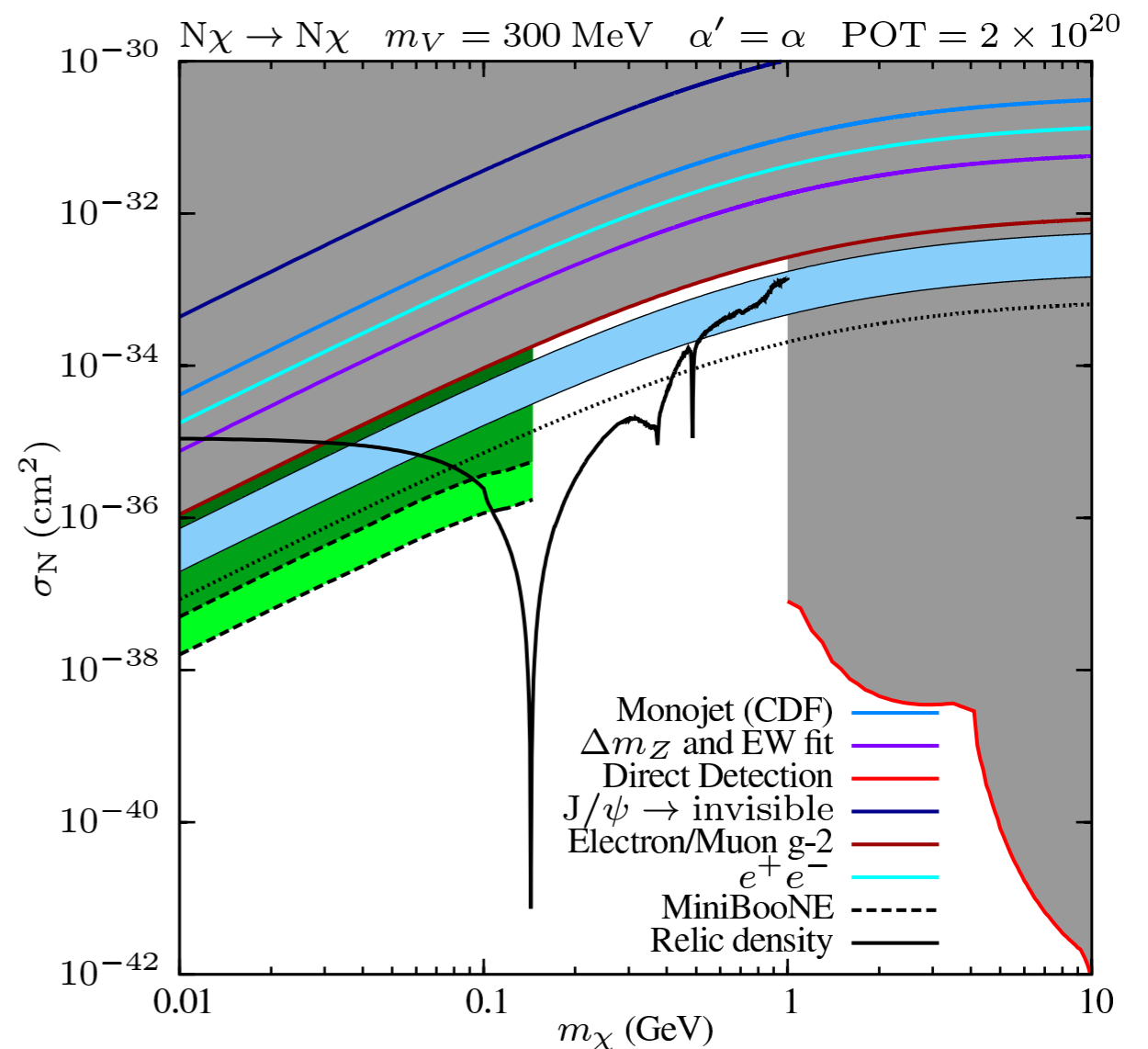
kinetic mixing

DM signal at MiniBooNE

Fixing the V mass and varying the DM mass:



baryonic V



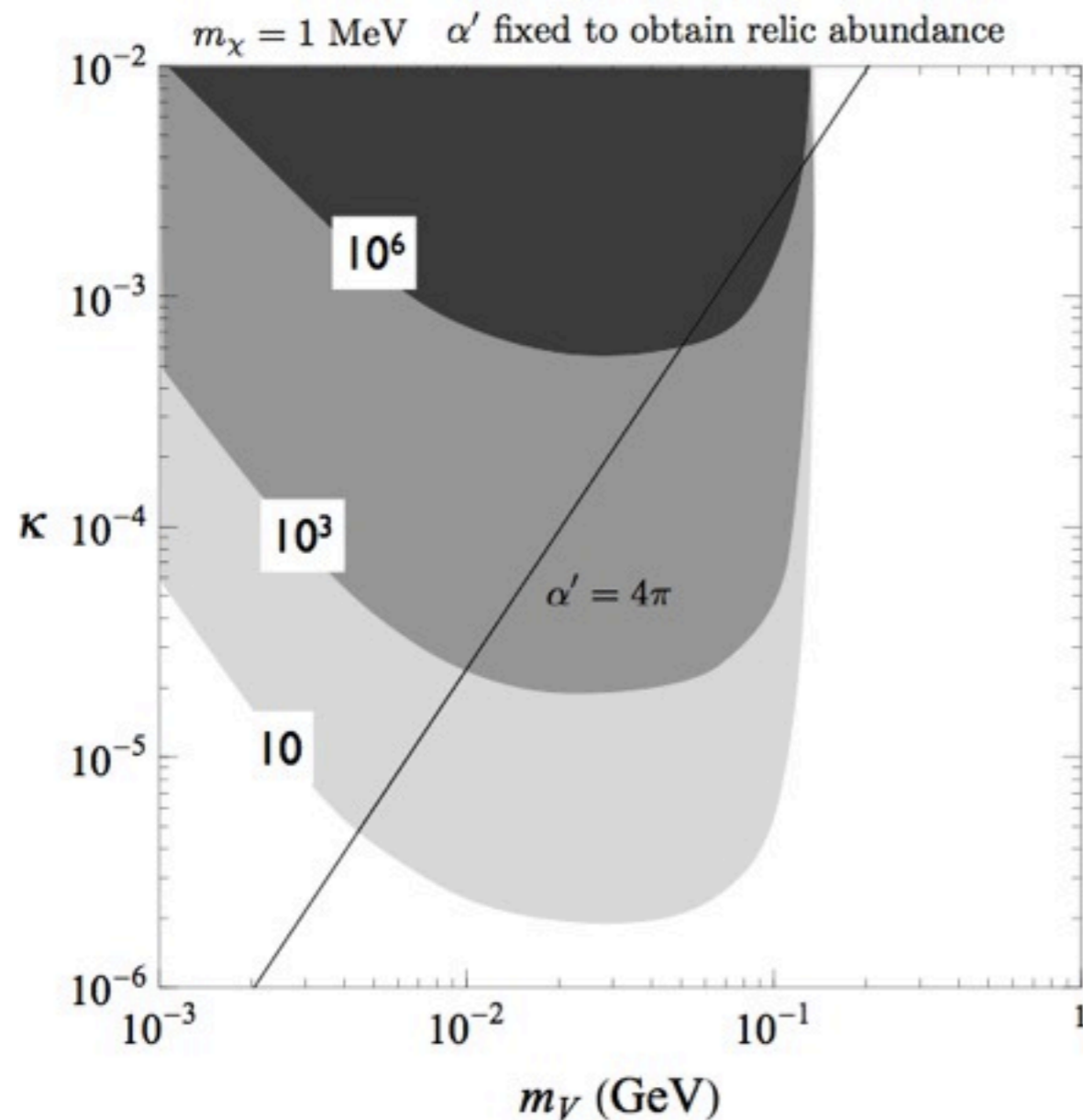
kinetic mixing

Other Experiments

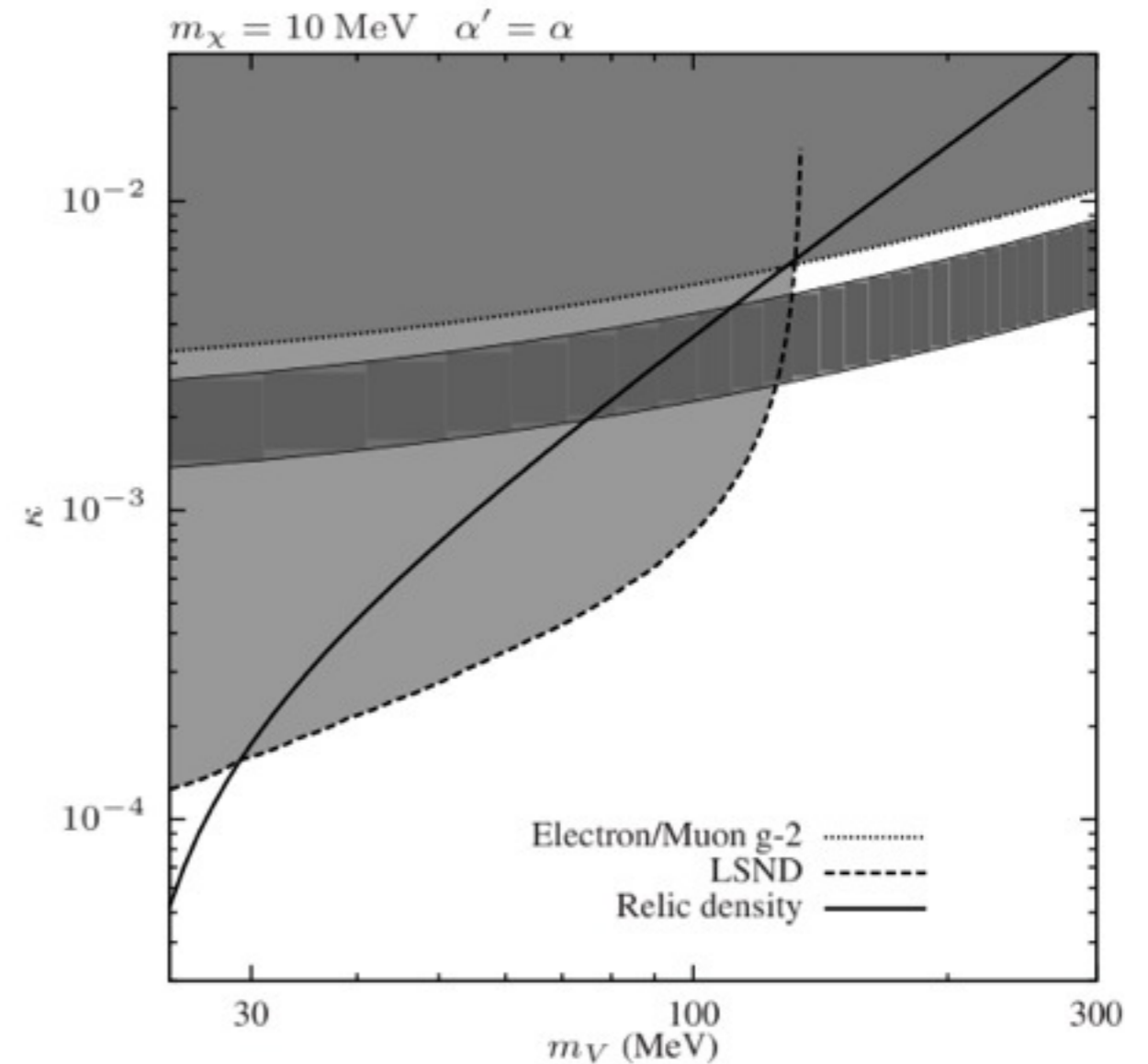
LSND

800 MeV p, 10^{23} POT

DM prod. through π^0 decay
NC scattering on electrons
170 T mineral oil detector
30 m off-axis



[Batell, Pospelov, Ritz '09]

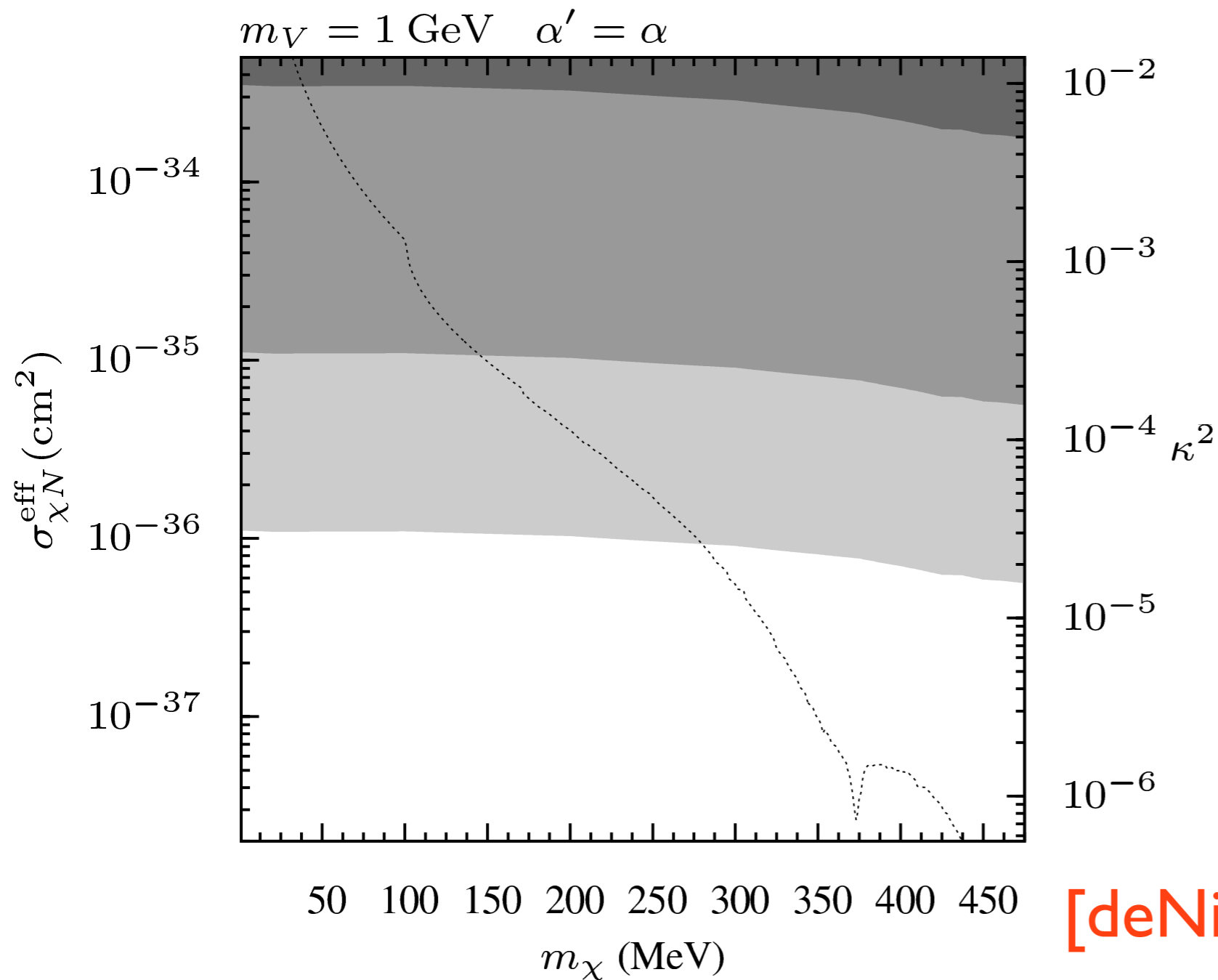


[deNiverville, Pospelov, Ritz '11]

T2K

30 MeV μ , 10^{21} POT

DM prod. through $q\bar{q}$
NC scattering on nucleons
ND280 280 m, 2.5° off-axis



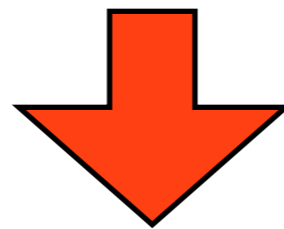
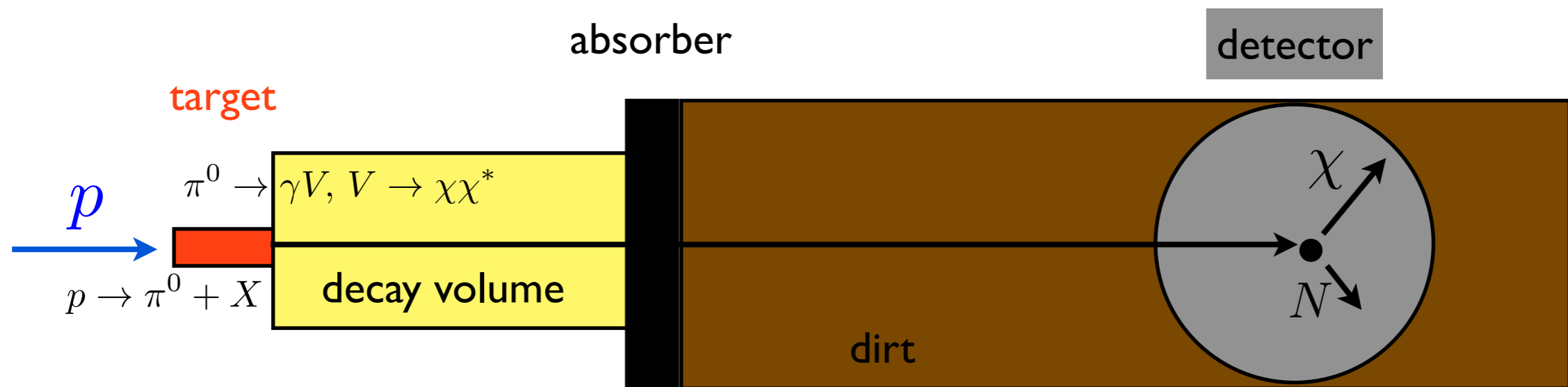
work needed to
disentangle from
backgrounds

possible \sim single
event sensitivities at
SuperK (295 km)
using timing, under
study

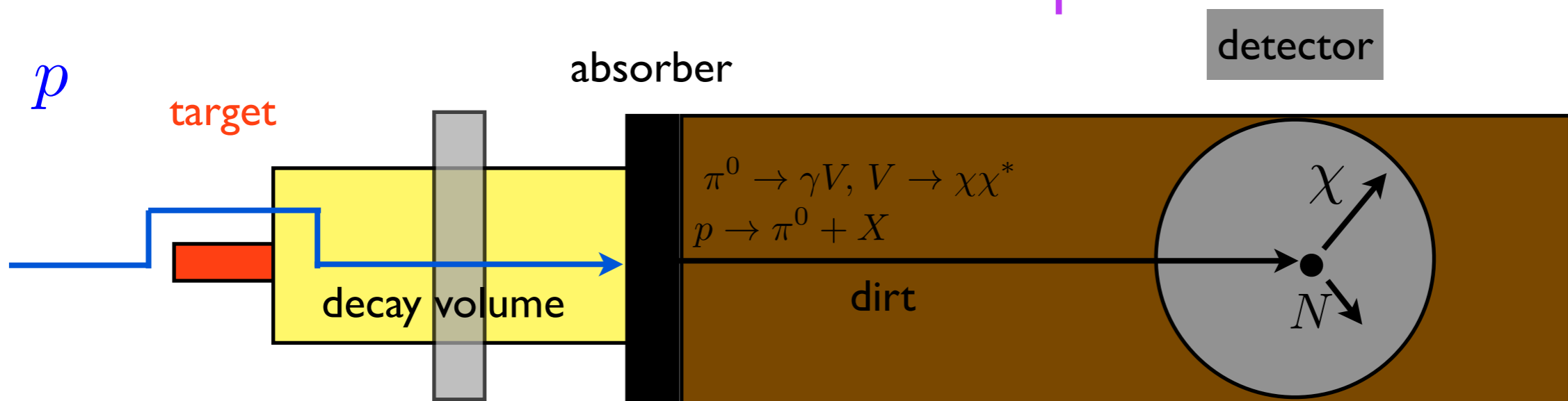
[deNiverville, McKeen, Ritz '12]

MINOS, NOvA, LBNE, E137, ... at this workshop

Optimizing Proton Beam Experiments



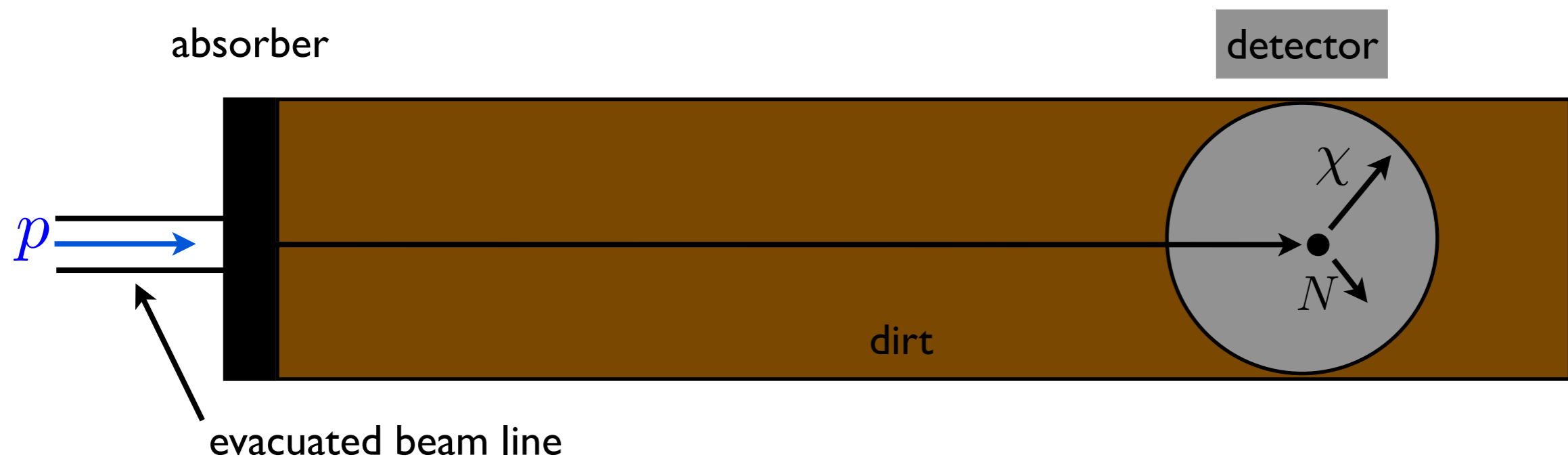
Steer beam into dump:



Proton-air collisions in decay volume produce neutrinos

Optimizing Proton Beam Experiments

Ideally, beam dump should be positioned immediately following beamline



Potential reduction of neutrino flux by 2-3 orders of magnitude!

Could also defocus charged particles that produce neutrinos with EM fields

Can't currently run in this mode at any neutrino experiment, needs work/planning

Outlook

Currently, we have no solid idea about how DM interacts (non-gravitationally) with the SM

We should have an open mind about DM mass, couplings to SM

If it is light and couples dominantly to quarks, **proton beam dump experiments are an ideal search environment**

Current analyses just getting started, new ideas welcome! Could be the start of a dedicated experimental program

Much work needed on model building (other ways to couple light DM to SM?) and “model independent” characterization of results

DM searches give a new, strong motivation to the experimental program at Fermilab, leveraging intense proton beams which are the foundation of the Intensity Frontier program

All neutrino oscillation experiments should be doing searches for DM and hidden sectors generally